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ACOUSTIC TECHNIQUES FOR THE NONDESTRUCTIVE EVALUATION OF ADHESIVELY BONDED COMPOSITE MATERIALS

by W. N. CLOTFELTER
Propulsion and Vehicle Engineering Laboratory

NASA

George C. Marshall Space Flight Center, Huntsville, Alabama

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ABSTRACT

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The extensive usage of composite materials in the Saturn vehicle has required considerable effort in the development of nondestructive inspection methods to evaluate the mechanical integrity of these materials. This report describes through-transmission and single-side acoustic methods applicable to the quality verification of composite panels. Some of the techniques discussed are "off the shelf." Others are believed to be unique. All of these inspection methods are discussed and illustrated to show their applicability to the quality verification of certain types of composite structure used in the Saturn. An attempt has been made to relate selected techniques to the acoustic characteristics of the materials used.

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER

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RESEARCH AND DEVELOPMENT OPERATIONS

PROPULSION AND VEHICLE ENGINEERING LABORATORY

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SUMMARY

The efforts to improve the strength to weight ratio of materials for application in the aerospace industry have resulted in the development of honeycomb sandwich materials. Probably the most difficult problem associated with these materials is the verification of their structural integrity nondestructively. Initial efforts have been placed on ultrasonic techniques which permit evaluation of the material without requiring access to both sides since, after installation into a vehicle, one side of the material may be either inaccessible or extremely difficult to reach. However, since problem solution is simplified if access to both sides of the material is available, experimental studies have been made using through transmission techniques. The work has established the practicality of determining the integrity of sandwich materials with both single side and two side techniques, thus permitting complete verification of sandwich material integrity both before and after installation into a vehicle. Not only has this been demonstrated for simple sandwich materials but also for complex sandwich materials which include such things as intermediate vapor barriers like those used in the dual seal cryogenic insulation material.

INTRODUCTION

The utilization of composite materials in the design of launch vehicle structures has signaled a major advancement in design technology. Already, composite materials have been used advantageously for several applications in launch vehicles. Furthermore, design studies have demonstrated several potential applications of composite materials which result in major vehicle weight saving without sacrificing performance. However, to assure maximum reliability in the structure, a need exists to develop nondestructive testing (NDT) techniques which can assure a high quality composite material. An application which illustrates the need for high quality in the composite material is the common bulkhead in vehicle tankage to separate two cryogenic propellants.

The upper stages (S-IV, S-IVB, and S-II) of both Saturn I and Saturn V utilize liquid hydrogen (LH_2) and liquid oxygen (LOX) as the fuel and oxidizer, respectively. In all three stages, a common bulkhead design is utilized in the separation of LH_2 and LOX. It is not the purpose of this paper to discuss the merits of the common bulkhead design; however, the advantages from the standpoint of vehicle weight and height are obvious when the common bulkhead is compared to two separate bulkheads. Furthermore, the utilization of a composite material in the bulkhead has obvious advantages over other design concepts when one considers that the bulkhead must serve both as a structure and as cryogenic insulation. However, the capability of a composite material to satisfy these conditions is dependent upon the quality of the material. Other composite material applications are predicted on the assumption that the material is essentially flawless, a condition which has not been demonstrated consistently. Four types of composite materials will be discussed in this paper:

a. Bonded honeycomb construction consisting of metal face sheets adhesively bonded to a reinforced plastic honeycomb core

b. The "double sandwich" type of construction consisting of metal face sheets, heat resistant phenolic and Mylar honeycomb cores separated by a thin metallic vapor barrier, and adhesively bonded together

c. Foam materials adhesively bonded to metal

d. Balsa wood adhesively bonded to steel.

Exploded views of the constituents of composites "a" through "d" are shown in FIG 1 through 4, respectively. Since the honeycomb materials are used in Saturn vehicles, most of the report will be devoted to methods of inspecting them. Early in the Saturn program, designers were considering foam and balsa wood composites for cryogenic insulation. Therefore, since these materials may be of interest to other organizations, a limited amount of space in the appendix will be given to this area. The appendix will also include additional information on honeycomb materials.

Obviously, no single inspection technique can be used to effectively evaluate all of these materials. Many techniques have been investigated with varying degrees of success. The most promising methods will be discussed in detail. Others will be evaluated in general terms.

Many variables are involved in the acoustic evaluation of composite materials of the honeycomb type. This is especially true in the case of non-metallic cores adhesively bonded to thin metallic face plates. The geometry of the core, large differences in elastic properties of core, face plates, and adhesives, and the complicated acoustic characteristics of thin plates make it difficult to predict inspection results theoretically. Thus, a dual approach has been followed in this development program. First, due to limited time, attempts have been made to find or develop inspection methods that could be used to accomplish the required materials evaluation tasks without too much attention being given to details of the phenomena involved. Secondly, some time has been spent in relating experimental results to the basic acoustic properties of the materials. Some interesting results of this work will be discussed.

AREAS OF INVESTIGATION

Through Transmission Techniques

1. Water Coupled Methods

Two major difficulties have been experienced by many people in the testing of large honeycomb structures with through transmission techniques: (1) the exact location of areas of debond cannot be determined with respect to depth, and (2) transducer alignment.

A technique has been developed to minimize this alignment problem and to improve information presentation on the oscilloscope (ref. 1). The referenced report describes a continuous wave inspection system consisting of a large 200 kc quartz transmitter and a 2.25 mc lithium sulphate receiver. An ordinary oscillator was used to energize the transmitter, and a reflectoscope processed the received signal. Good inspection results were obtained with the transducers misaligned by three or four inches. Subsequently, the quartz transducer has been replaced with an air backed PZT type. Better specimen-penetration and a range of frequencies can be obtained with the PZT transducer, which is illustrated in FIG 5. C-scan recordings that depict well defined areas of debond have been made by using this technique. A typical example of honeycomb debond is shown in FIG 6. Although no satisfactory solution has been found to the problem of depicting the exact location of a defect with respect to depth by using through transmission techniques, recent improvements have been made which are helpful.

The PZT transducer described above operates well in a wide range of selected frequencies. This transducer has been especially useful in the inspection of composite materials of the metal-foam type. A liquid lens has been used to shape the sound field. The beam can be made wide when probe alignment is a problem, or it can be made sharp for increased penetrating power. Figures 7 and 8 show typical beam profiles that were obtained with a PZT transducer and a liquid lens.

Perhaps the most significant improvement in through inspection techniques is the demonstration or proof that certain acoustic properties of thin honeycomb panels are exactly the same as those of thin solid sheets having the same thickness/wavelength ratios. Panels are described as "thin" in terms of the wavelength of sound in the specific specimen. Details are discussed below.

The acoustic characteristics of thin sheets of material have been well established (ref. 2). Rayleigh did mostly theoretical work (ref. 3) R. W. Boyle, T. F. Lehmann, and others performed laboratory measurements yielding the following information. The relative amounts of acoustic energy reflected, transmitted, and absorbed when sound waves impinge on a thin plate are determined by the angle of incidence, the acoustic impedance of the plate, the acoustic impedance of the coupling medium, and the thickness of the specimen. Material thickness loses much of its significance when the specimen is several wavelengths or more thick. A formula for the special case of thin plates and normal incidence of sound is given below.

$$R = \frac{\left(\frac{V_1P_1}{V_2P_2} - \frac{V_2P_2}{V_1P_1}\right)^2}{4\cot^2\frac{2\pi d}{\lambda} + \left(\frac{V_1P_1}{V_2P_2} + \frac{V_2P_2}{V_1P_1}\right)^2}$$

where:

R = Ratio of reflected to incident energy

V_1 = Velocity of sound in first medium or water

V_2 = Velocity of sound in second medium

P_1 and P_2 = Density of first and second mediums, respectively

d = Thickness of plate

λ = Wavelength of sound in specimen

Acoustic impedance is equal to the velocity of sound in a medium times the density of the medium. This is true for any material thickness. The special acoustic characteristic of thin plates, which is their frequency sensitivity, is explained by the expression "$4\cot^2\frac{2\pi d}{\lambda}$" in the formula above.

Honeycomb panels with HRP cores which are adhesively bonded to thin metal face sheets are also very frequency sensitive. This is true for both through transmission and pulse echo techniques. Pulse echo techniques are discussed later. In the case of through transmission, the frequency sensitivity is related to the combined metal, adhesive, and honeycomb thickness of the panel in exactly the same manner as for solid panels of the same thickness/wavelength ratio. Figure 9 illustrates this. As observed from the formula, the reflected energy varies from zero when the specimen is a half wavelength thick to a maximum for specimen thickness of $\frac{\lambda}{4}$ or an odd multiple of $\frac{\lambda}{4}$. Of course, transmitted values are just opposite. The best through transmission flaw detection is obtained when frequencies are chosen to make the specimen thickness equal to a half wavelength or a multiple of the half wavelength. Since maximum transmission then is obtained for a well bonded specimen, a greater change is observed when a debond occurs than for other frequencies. The significant point is not to select frequencies near the $\frac{\lambda}{4}$ value since attenuation is high even for well bonded composites.

The discussion above indicates that the velocity of sound through composite panels can be measured in the same way that velocity is measured in thin solid plates. Since velocity = f, it is only necessary to measure specimen thickness and to determine the lowest frequency that can penetrate the panel with near zero attenuation to determine the velocity. This lowest frequency is equal to a half wavelength of sound in the material. Thus, only a simple calculation is required. However, care should be exercised because multiples of this lowest frequency also penetrate well. Perhaps this through transmission technique could be developed so that the exact location of debonds could be determined with respect to depth in a panel. Since through transmission of this type cannot be used after the bulkhead is installed in the vehicle, experimental development of this approach was stopped to allow time for other work.

2. Air Coupled Through - Transmission Inspection Techniques

A cryogenic insulating material that is composed of two layers of honeycomb core separated by a vapor barrier has been developed at the Marshall Center and designated "dual seal insulation." An exploded view of this is shown in FIG 2. This composite material is very light and has very good thermal properties. However, techniques that are used to inspect composites with HRP type cores were found to be inadequate for this insulation. Experiments established the difficulty of penetrating this material with high frequency sound by using conventional ultrasonic equipment. Mylar honeycomb caused most of the high frequency attenuation. Penetration could be obtained to a limited extent with some of the lower ultrasonic frequencies, but debond detection was very poor. Most of this difficulty was due to the complex structure of the panel, but part was due to the rough surface on one side of the material. Therefore, a new approach was made which involved air coupled sound generators such as sirens, loud speakers, air jets, and air backed crystals. Receiving transducers which were investigated included microphones, ultrasonic leak detectors, and crystals. Initial tests were not successful; not enough difference could be obtained between the attenuation of a well bonded specimen and one containing debonds. It was theorized, which later proved to be correct, that the energy level of these low frequency signals was too high since audio frequencies penetrate easily. When the power of the transmitters was cut and increased amplification was provided in the receiving circuit, good results were obtained. Typical oscilloscope patterns are shown in FIG 10. The advantages of air coupling are numerous. As shown in FIG 11, one surface of the panel is very rough. Air coupling eliminates variable contact problems as well as water, grease, and other couplants. Transducer alignment difficulties are eliminated since a transmitter can be placed in the center of a tank remaining in a fixed position as receivers scan the outside.

Although good results have been obtained with a very limited number of specimens in the laboratory, more work is needed. The receivers should be more sensitive and made frequency selective by the addition of variable band pass filters. Sound generators should be carefully evaluated in terms of the relative amplitude of various frequency components.

Single Side Inspection Techniques

1. A Swept Frequency Method

Very limited success was attained in inspecting honeycomb panels with the Coindascope.* It is not difficult to determine the presence or the absence of a bond at the metal-adhesive interface; however, the large change in acoustic impedance makes it much more difficult to evaluate the adhesive-honeycomb core bond for composites with non-metallic cores. Because of this difficulty, the problem of wave shape interpretation, and the requirement for "C-scan" records, this instrument is considered unsatisfactory as the major inspection device for common bulkheads in the Saturn vehicle.

2. The Inspection of Composite Panels With Surface Waves

An effective technique for spot checking honeycomb panels involves the absorption of surface waves by adhesive bonds. Two transducers are mounted so that one can receive energy which is transmitted by the other. When these transducers are properly coupled to a specimen, debonds are indicated by an increase in the received energy since good bonds absorb the sound. This is illustrated in FIG 14. The major requirements include good coupling and wavelengths that are greater than the thickness of the face sheet. Both bond lines can be inspected this way. Theoretically, it should be possible to determine which interface is not bonded by changing the frequency of the surface waves; however, the limited amount of work done in the area has not demonstrated this. Although surface waves show much promise, this method will not be considered practical for a major bulkhead inspection tool until better coupling and scanning techniques can be developed.

Figures 12 and 13 show simulated defects after separation of the skin from the core. Figure 14 shows photographically the positive indications of debonds which are obtained with surface waves.

3. A Double Probe Technique

Several companies build transducers containing two crystals which are side by side. These crystals are connected independently to a transmitter and to a receiver of ultrasonic energy. When the probe is applied to the surface of a panel over a well bonded area, a minimum of

* Tradename, Pioneer Industries, Division Almar-York Company, Inc., 3455 West Vickery Boulevard, Fort Worth, Texas

energy will be reflected into the receiver. When a debond occurs, a greater percentage of the incident energy is reflected. Debonds at both interfaces may be located with this technique; however, it is difficult to determine if the defect is near the skin or near the core.

Oscilloscope patterns are shown in FIG 15 for well bonded and for defective areas of a honeycomb panel. These oscilloscope patterns are of the panel which is shown in FIG 12 and 13. A limited number of C-scan recordings have been made using this technique. Although fair records were obtained by using this double transducer technique, it is considered more suitable as a spot checking method. More work is needed in this area.

4. Pulse Echo Techniques

Usually, a front surface reflection, a back surface echo, and intermediate reflections from defects are expected when pulse echo techniques are used. Reflections from a honeycomb panel are entirely different. It is extremely difficult to obtain echoes from the back side of the panel because both adhesive materials and honeycomb absorb so much sound. Echoes from the front surface, from the back surface of the face plate, and from the adhesive layer merge when thin plates are used and make it difficult to resolve amplitude differences because of small debonds. Some debonds between the face plate and adhesive layer can be detected, but, in general, the simple pulse echo technique is unsatisfactory for the inspection of materials with non-metallic honeycomb cores.

When pulsed radio frequency energy is replaced with single sharp pulses, better resolution of the first boundary defects is obtained as shown in FIG 16.

5. A Combination Method Based on Damping and Impedance Variations

As indicated before, the acoustic characteristics of thin plates and panels have been well established. A formula describing these characteristics is repeated here for convenience.

$$R = \frac{\left(\dfrac{V_1P_1}{V_2P_2} - \dfrac{V_2P_2}{V_1P_1}\right)^2}{4\cot^2\dfrac{2\pi d}{\lambda} + \left(\dfrac{V_1P_1}{V_2P_2} + \dfrac{V_2P_2}{V_1P_1}\right)^2}$$

where:

R = Ratio of reflected to incident energy

V_1 = Velocity of sound in coupling medium

V_2 = Velocity of sound in second medium

P_1 and P_2 = Density of first and second mediums, respectively

d = Thickness of plate

λ = Wavelength of sound in specimen

A study of the formula shows that when plate thickness is equal to a half wavelength of sound within the plate maximum energy will pass through. When specimen thickness is a quarter wavelength or an odd multiple of a quarter wavelength, maximum energy will be reflected from the surface.

A method of evaluating honeycomb materials from one side has been developed which can be explained by the acoustic characteristics of thin plates indicated above. However, panels which are composed of thin metal sheets adhesively bonded to honeycomb cores present a problem more involved than the case for a single sheet. However, the formula expressed above still explains most of the experimental results, even in this more complicated specimen.

Thus, the best method of evaluating HRP honeycomb panels from one side is based on resonance phenomena and acoustic impedance variations although pulse echo equipment is used.

Details of this technique are depicted in FIG 17, 18, and 19. The oscilloscope pattern of FIG 19a illustrates the case of a well bonded panel. The first and second gates would indicate signal changes if debonds at the metal-adhesive and adhesive-core interfaces, respectively, should exist. Figure 19b shows the effect due to a metal-adhesive debond. Metal thickness in this case is almost exactly a half wavelength, so undamped plate resonance produces a ringing effect. An example of adhesive-core debond is shown in the second gate of FIG 19c. Notice that little change occurs in the first gate since well bonded adhesive dampens the ringing effect. However, since the metal face plate is a half wavelength thick, maximum energy is available at the metal-adhesive interface to penetrate the adhesive. Thus, this increased reflection at the second gate is simply due to the fact that no bond exists at the core to absorb this increased flow of energy through the face plate and adhesive, so it is reflected. Expressed differently, the acoustic impedance of the whole panel, not just the elastic properties of the metal face plate, affects the ratio of reflected to incident energy. The increasing difference between bond and debond conditions with each successive echo is best explained by the shift in acoustic impedance. Since the core does not absorb energy when a debond exists, the exponential decay of reflected energy is less steep, and a greater change in reflected energy occurs between the bond and debond conditions with each successive echo. Thus, the seventh or eighth echo is gated to obtain the C-scan recordings.

Figure 20 is a C-scan recording of HRP panel number 10. The top scan represents defects near the metal, and the lower picture indicates debonds near the core. The large center debond is shown on both scans, as it should, since it is not bonded to either surface. For best results, this technique required two recording channels.

CONCLUSIONS

The investigation which has been described in this report demonstrates that acoustic techniques can be developed for the effective nondestructive evaluation of complex adhesively bonded materials. This is especially significant when the composites are characterized by high sound attenuation and by large variations in acoustic impedance of the component materials.

When composite panels containing HRP honeycomb core are to be inspected, the combination technique is recommended. Although a specimen must be scanned from both sides (one side at a time), the exact location of a defect with respect to depth within the panel can be determined. Standard ultrasonic instrumentation can be used, and C-scan recordings are easily obtained. If there is any doubt about the exact condition of specific areas of a specimen, spot checks can be made. Either the surface wave or the double probe technique may be used effectively for these spot evaluations.

A limited amount of time has been spent in developing techniques for the inspection of "Dual Seal Insulation." This work clearly indicates that audio frequency techniques can be developed for this purpose.

Efforts are being directed presently toward methods of inspecting all of the interfaces of an HRP panel from a single side and the refinement of the audio frequency techniques for the inspection of "Dual Seal Insulation."

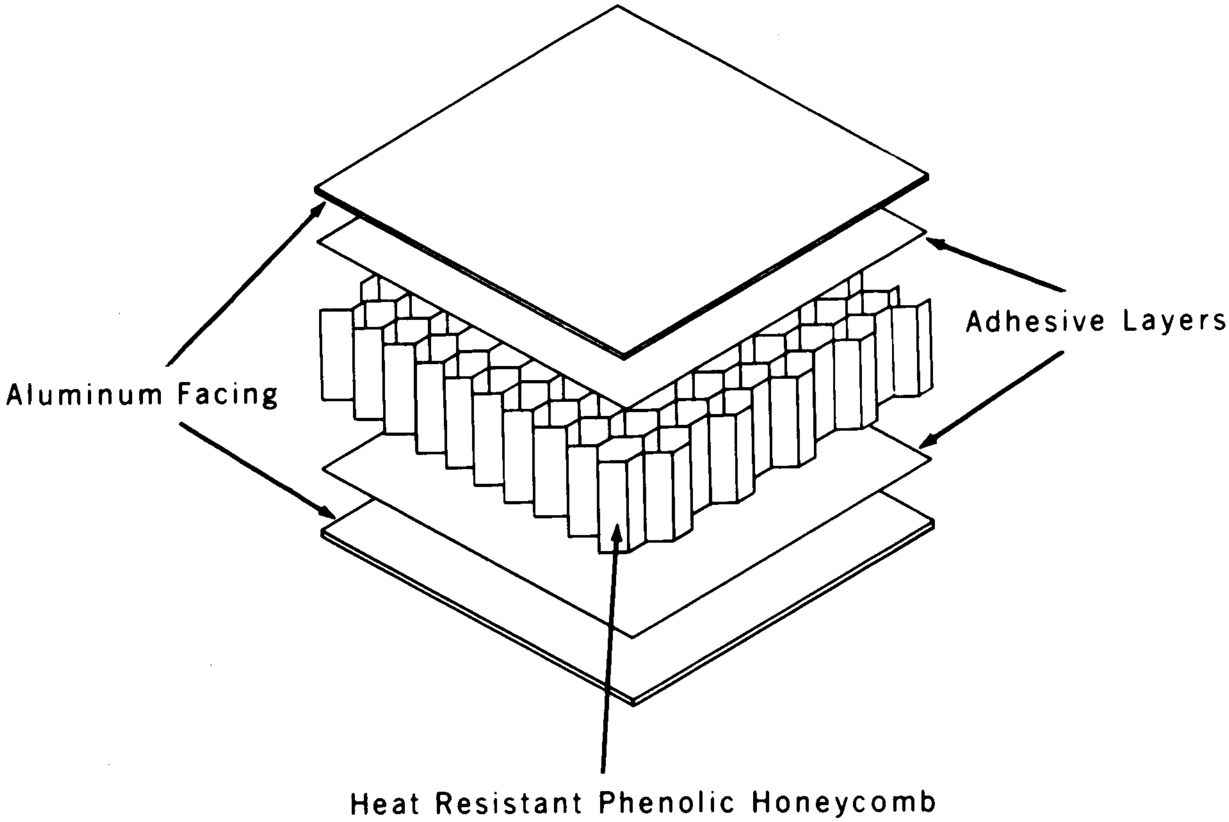


FIGURE 1 MATERIAL DESIGN FOR COMMON BULKHEADS

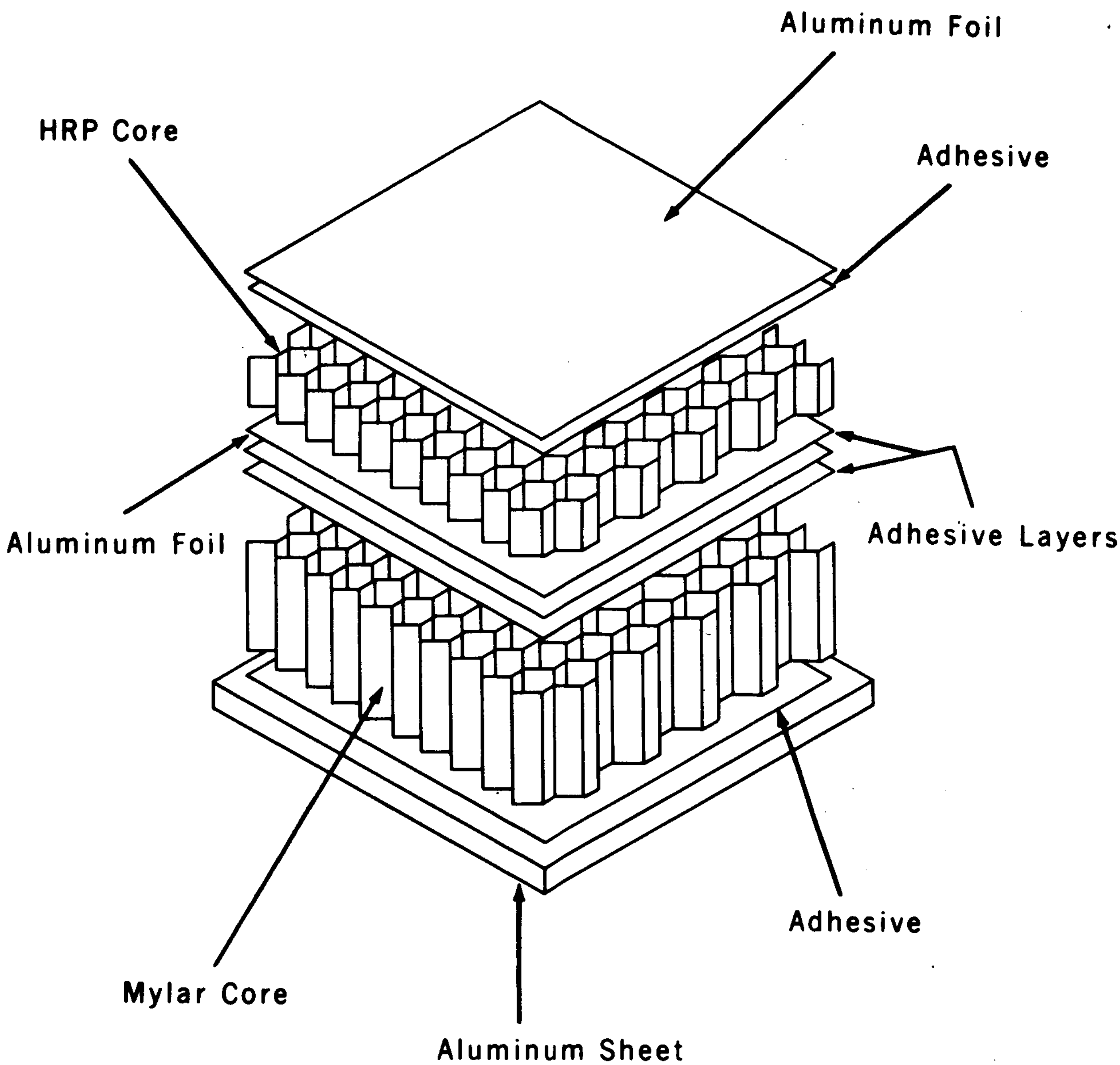


FIGURE 2 DESIGN OF DUAL SEAL INSULATION

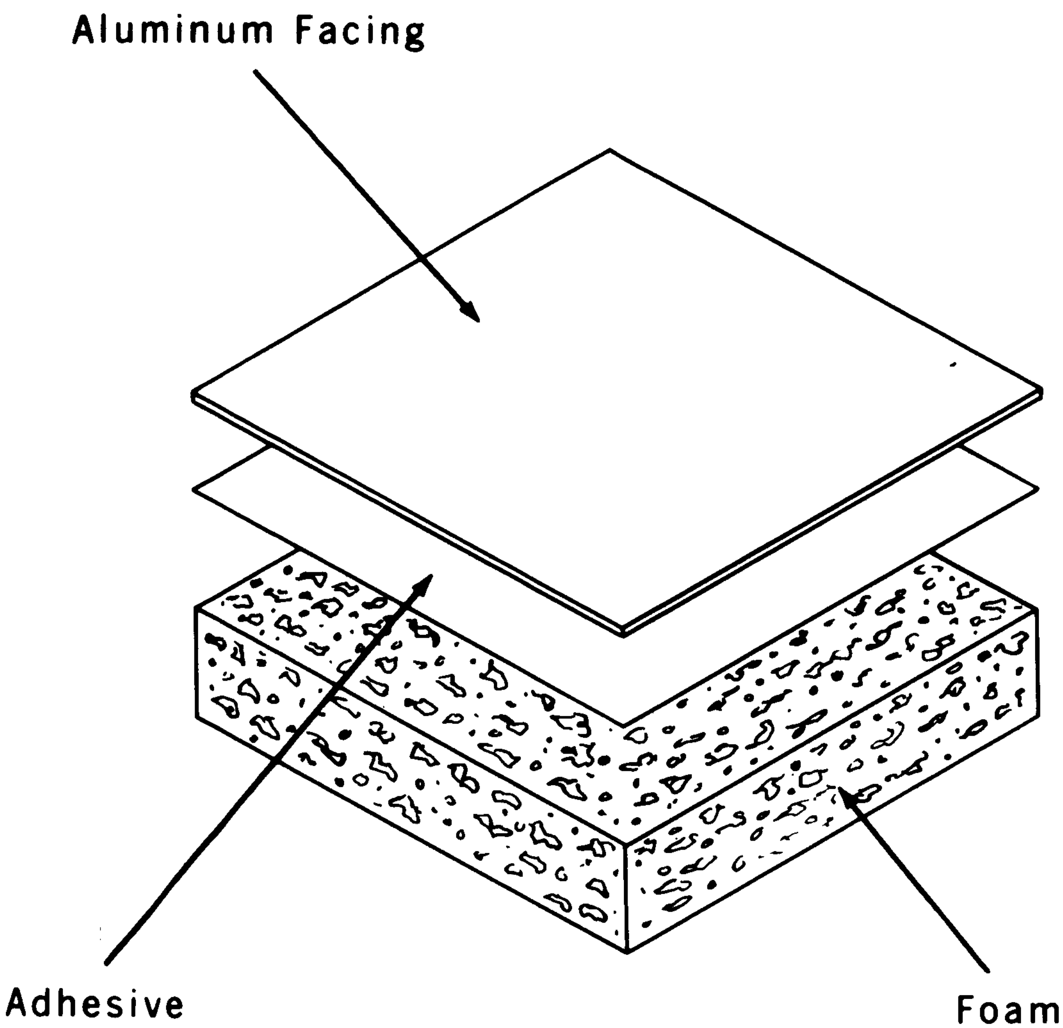


FIGURE 3 FOAM INSULATION

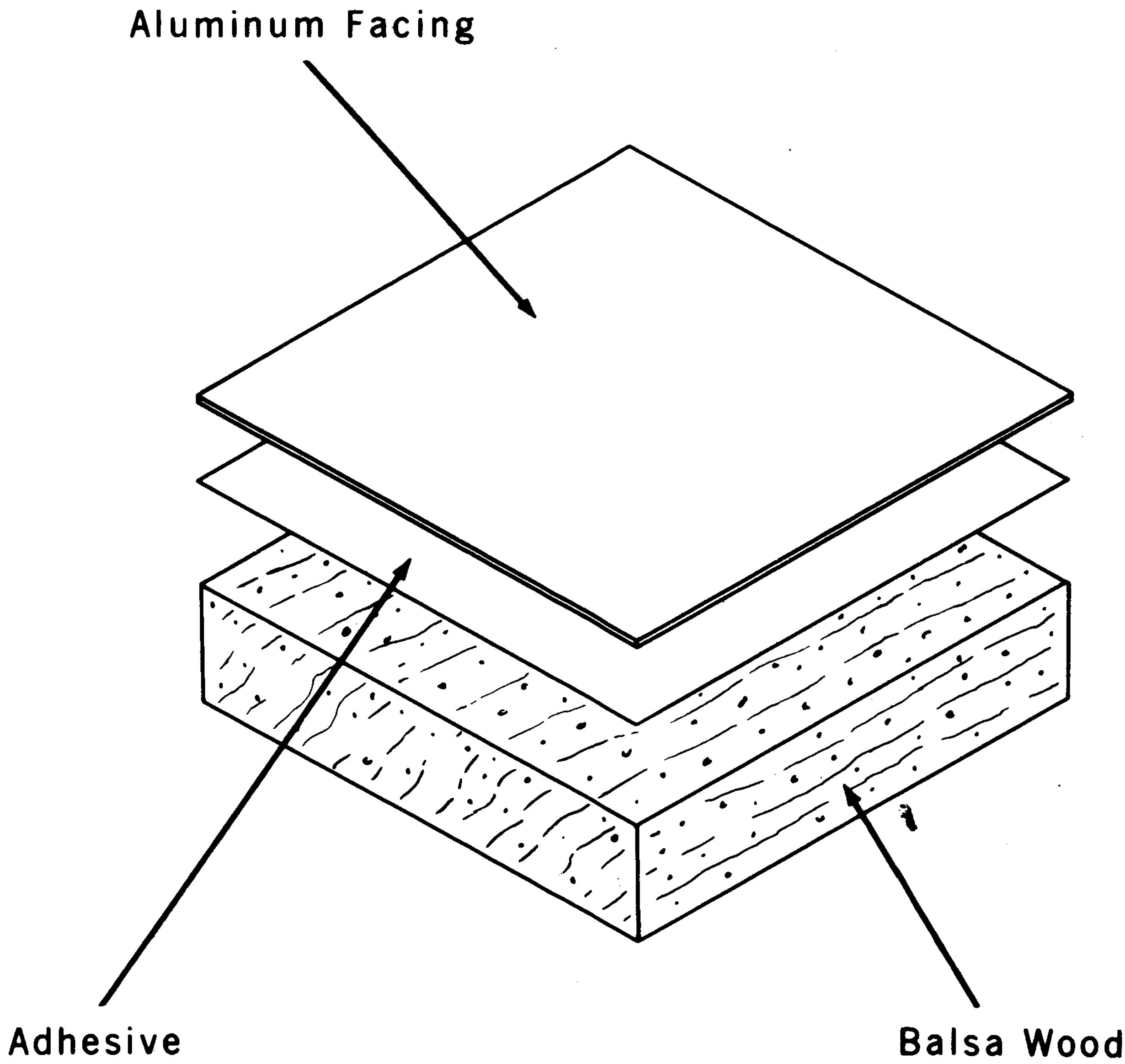


FIGURE 4 BALSA WOOD INSULATION

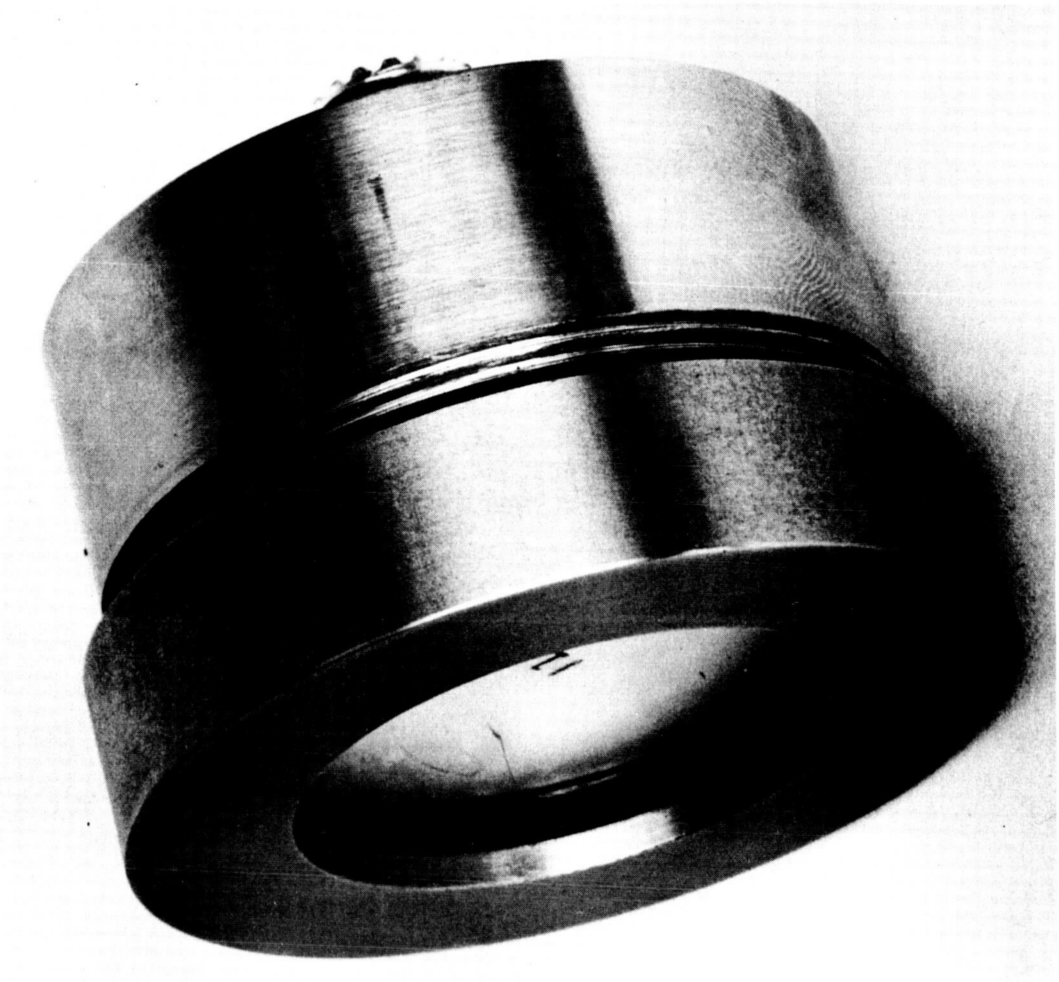


FIGURE 5a AIR BACKED PZT TRANSDUCER

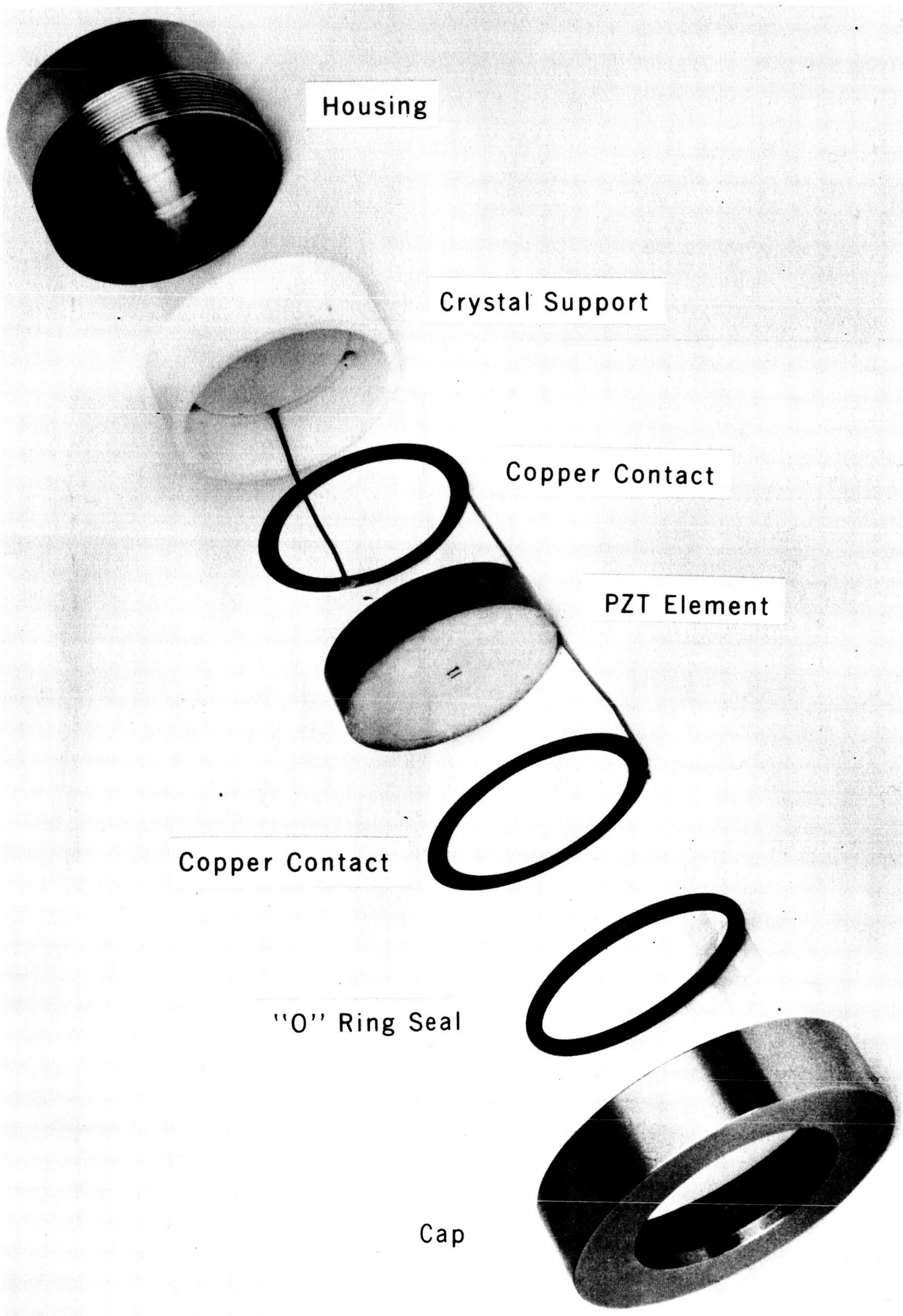


FIGURE 5b DETAILS OF PZT TRANSDUCER

FIGURE 6 A TYPICAL "C-SCAN" RECORDING

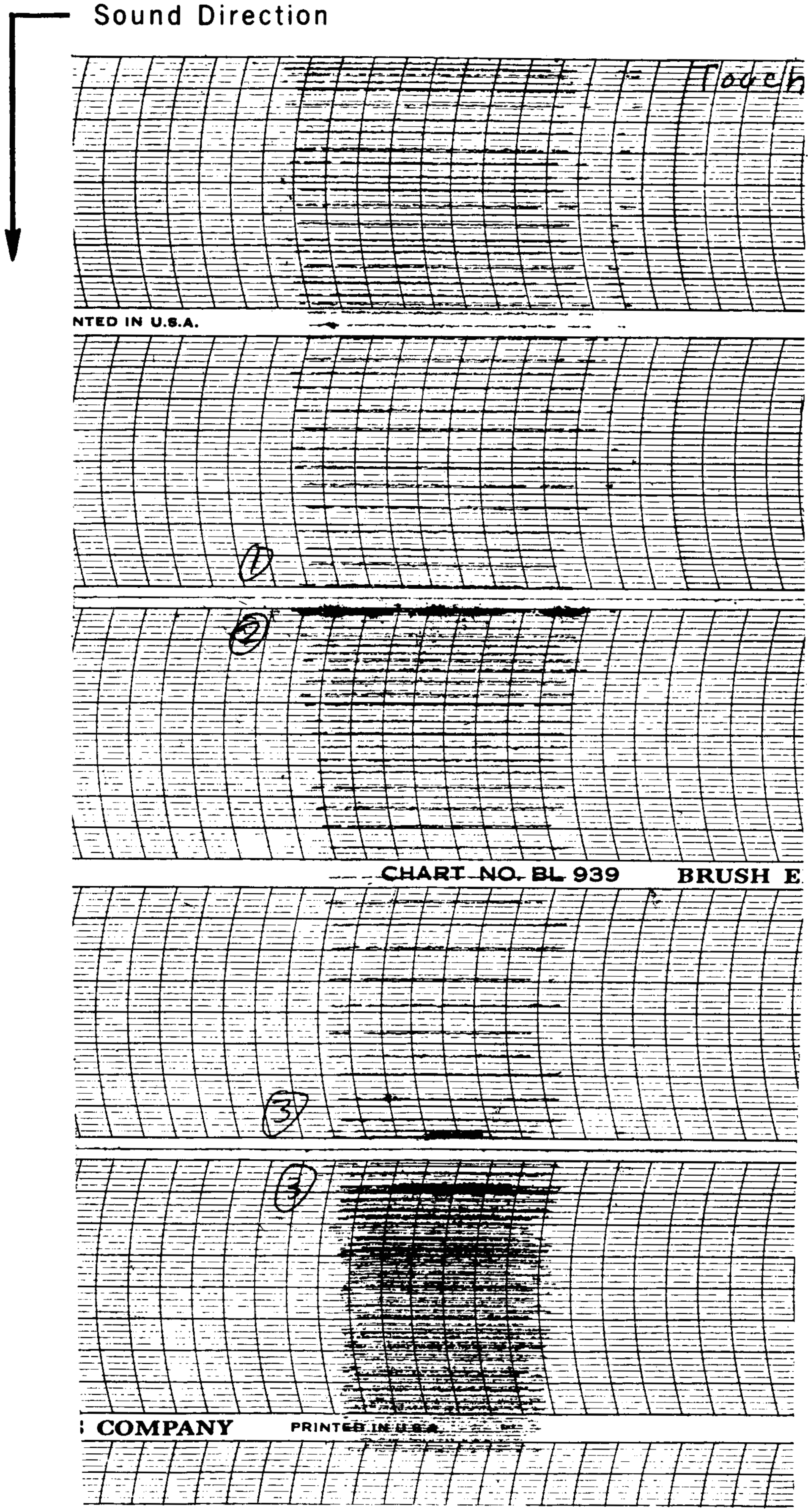


FIGURE 7 A MODIFIED SOUND FIELD

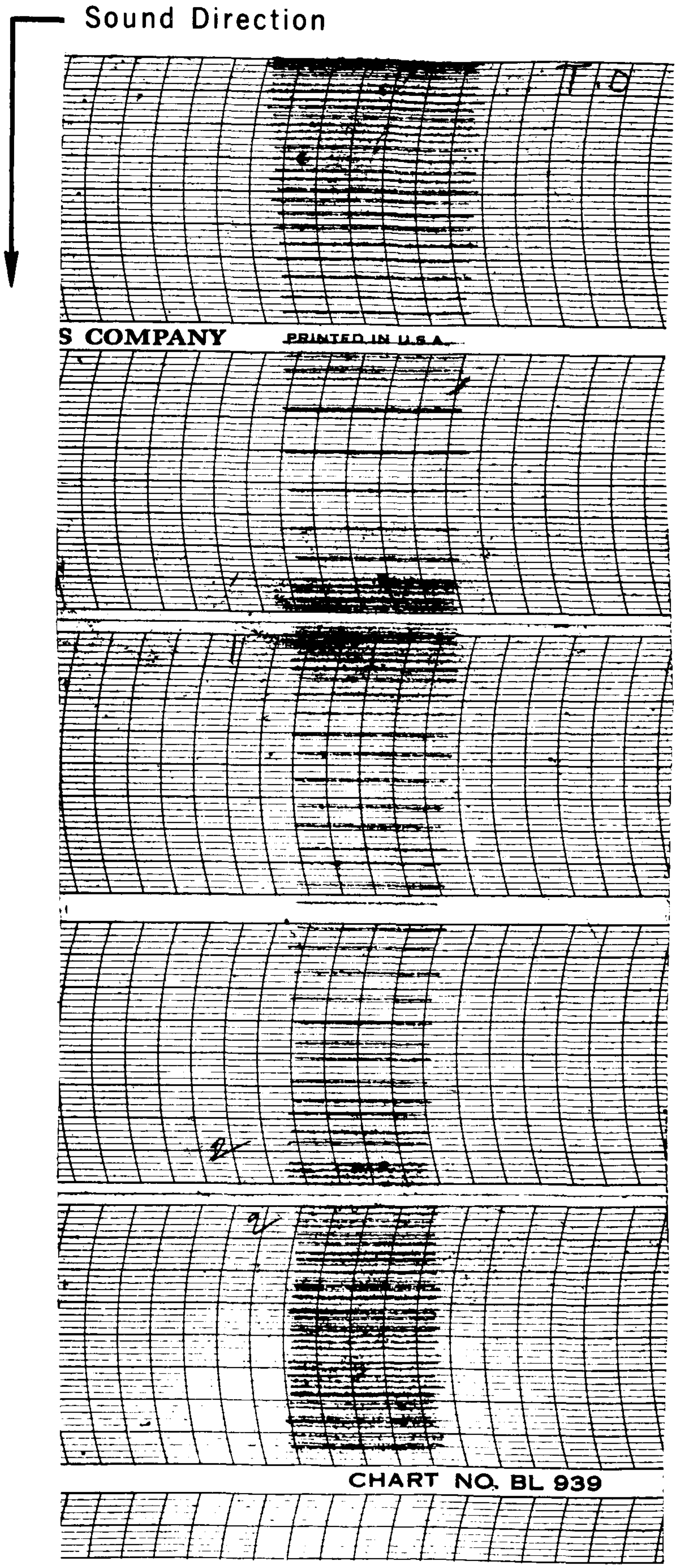
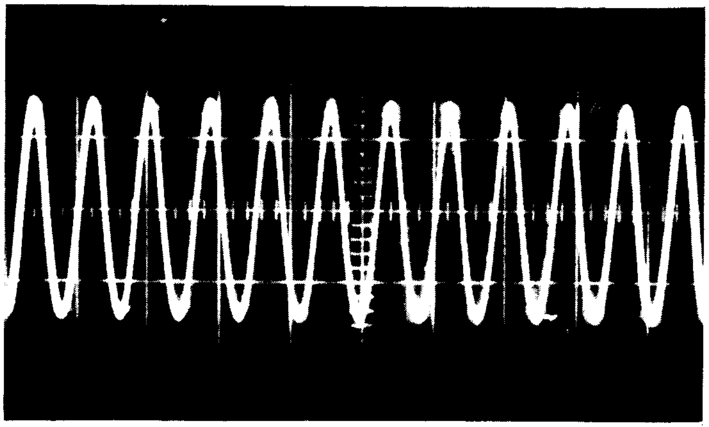


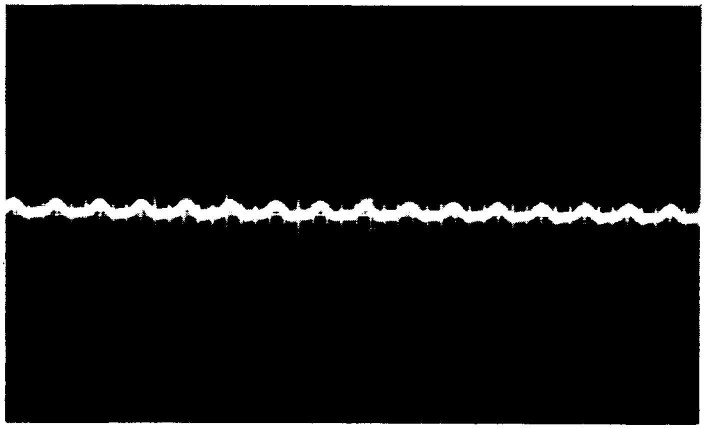
FIGURE 8 A SHARPLY MODIFIED SOUND FIELD

Plate Thickness

$t = \frac{\lambda}{2}$



$t = \frac{3\lambda}{4}$



$t = \lambda$

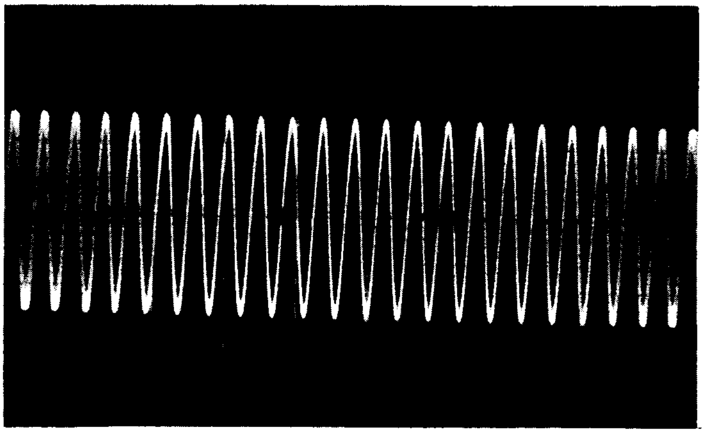
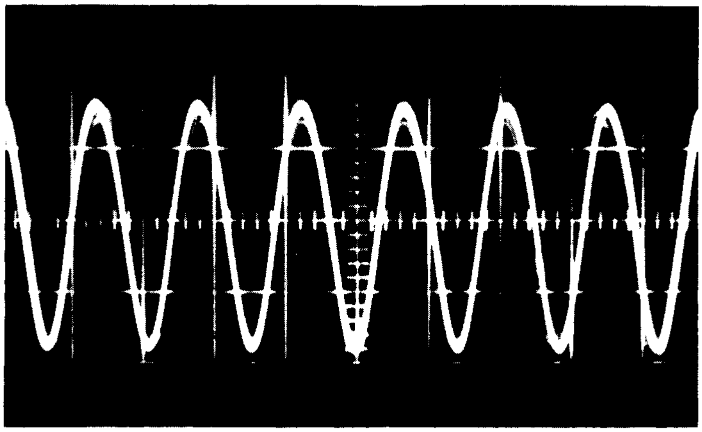
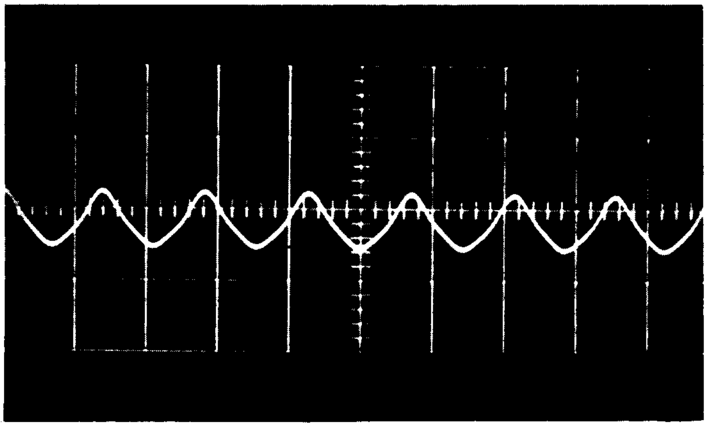


FIGURE 9 ACOUSTIC ATTENUATION IN THIN PLATES



a. Good Bond



b. Poor Bond

FIGURE 10 AN "A" SCOPE EVALUATION OF DUAL SEAL INSULATION

FIGURE 11 SURFACE CONDITIONS OF DUAL SEAL INSULATION

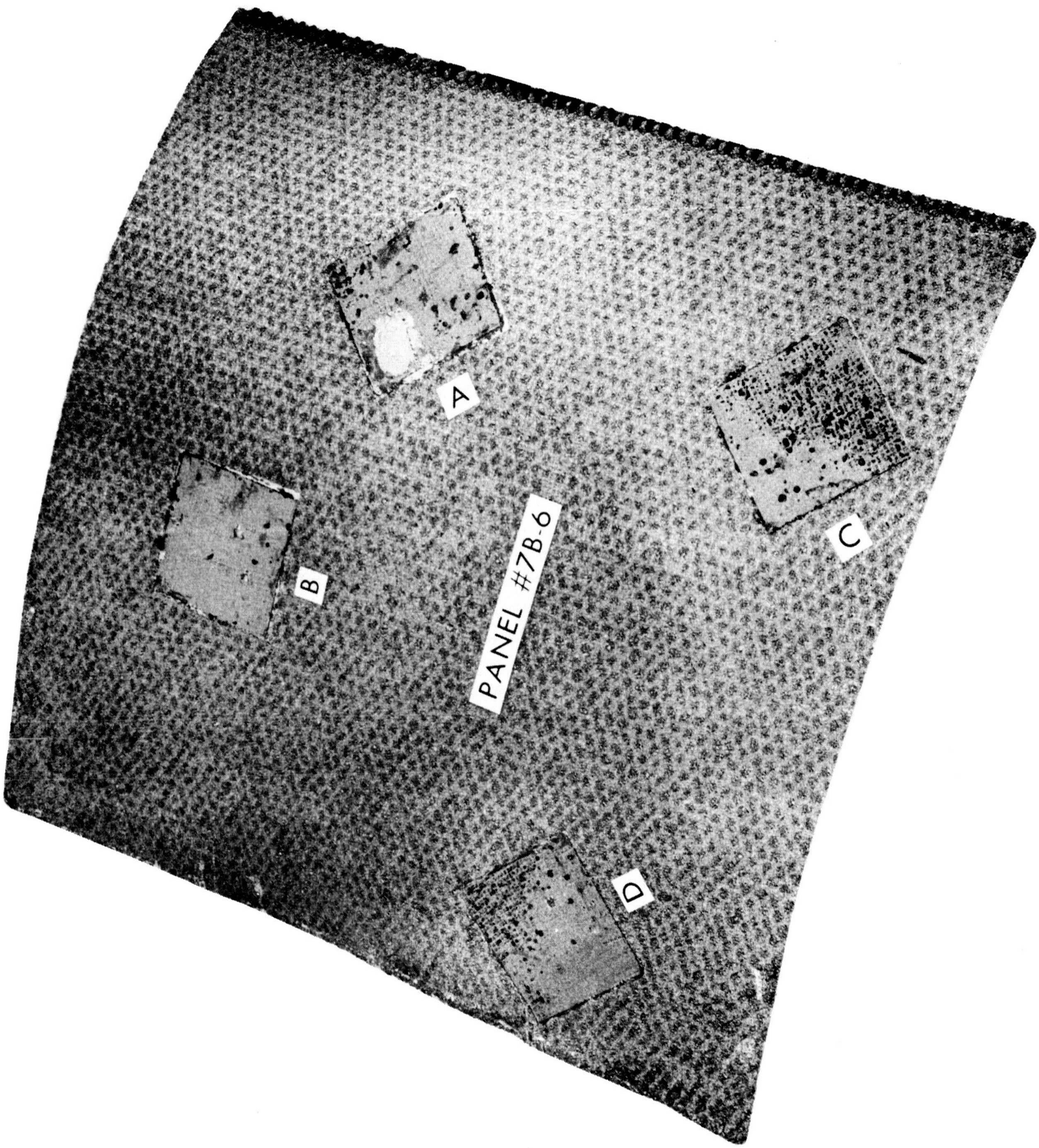


FIGURE 12 DESTRUCTIVE EVALUATION OF A HRP PANEL (COVER PLATE)

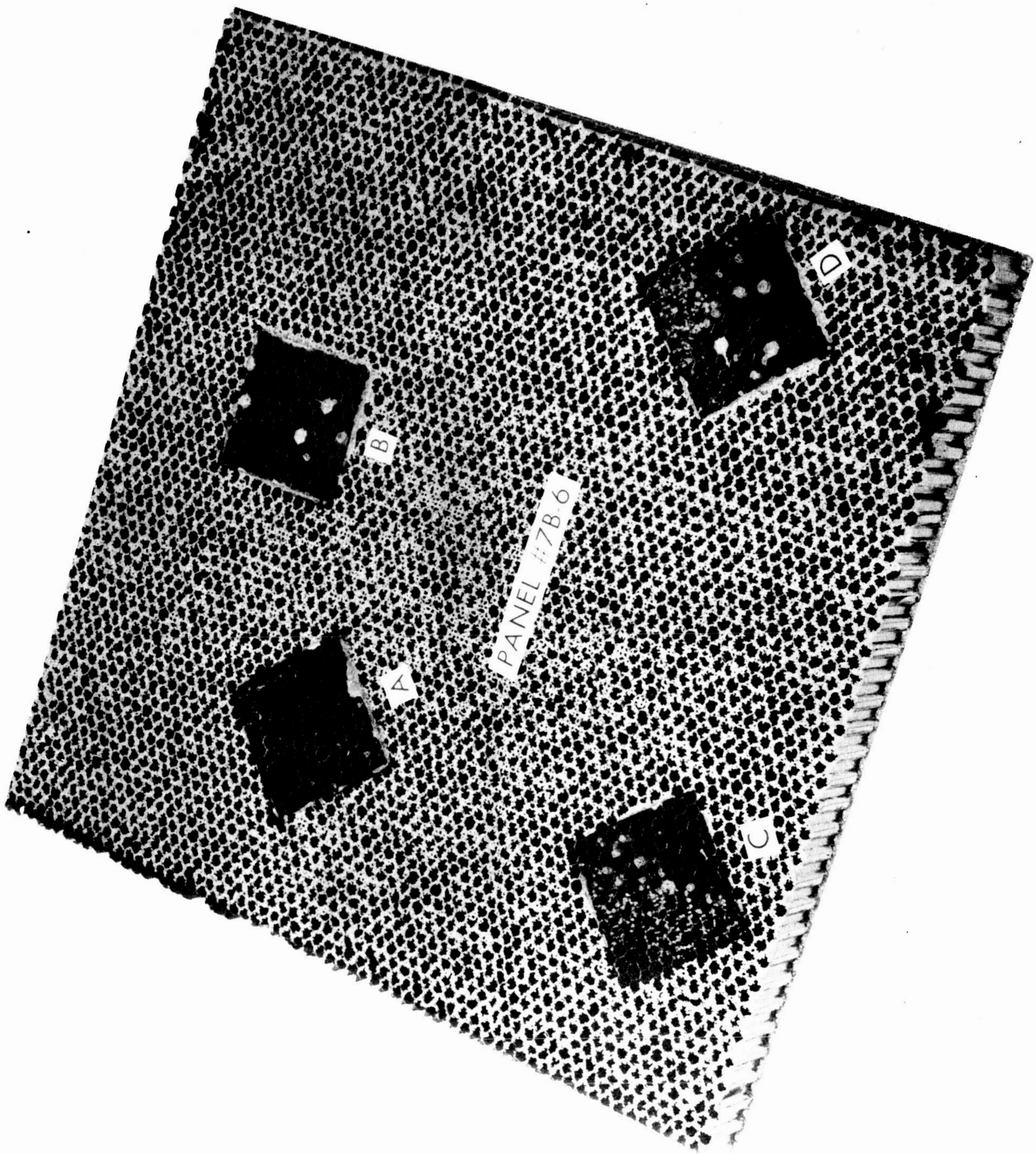
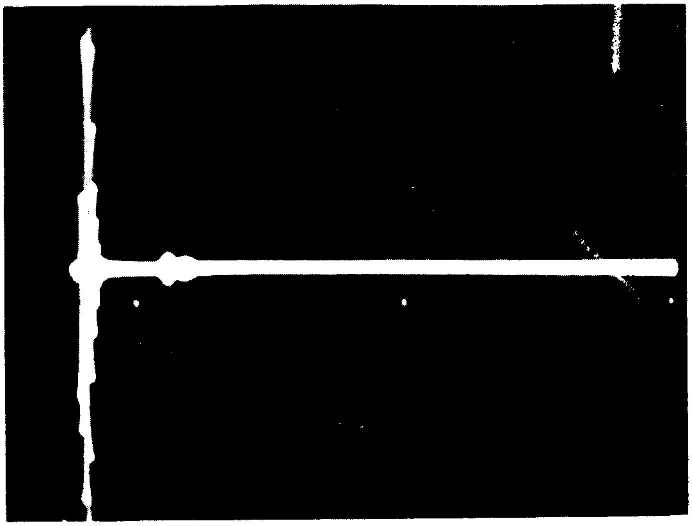
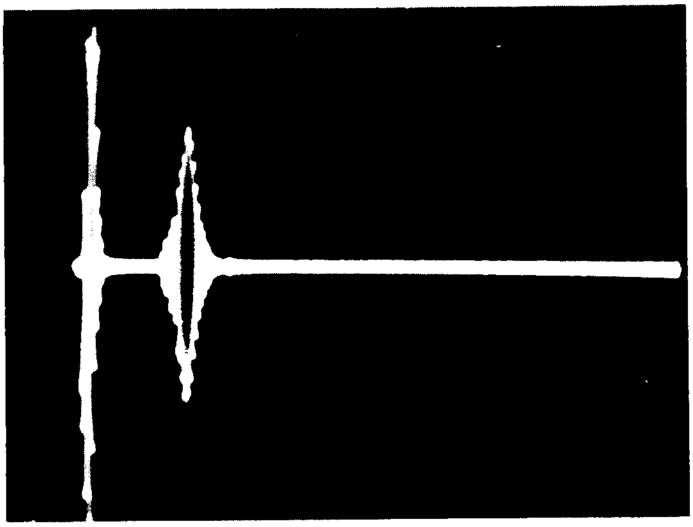


FIGURE 13 DESTRUCTIVE EVALUATION OF A HRP PANEL (HONEYCOMB)

Good Bond



Debond



Debond

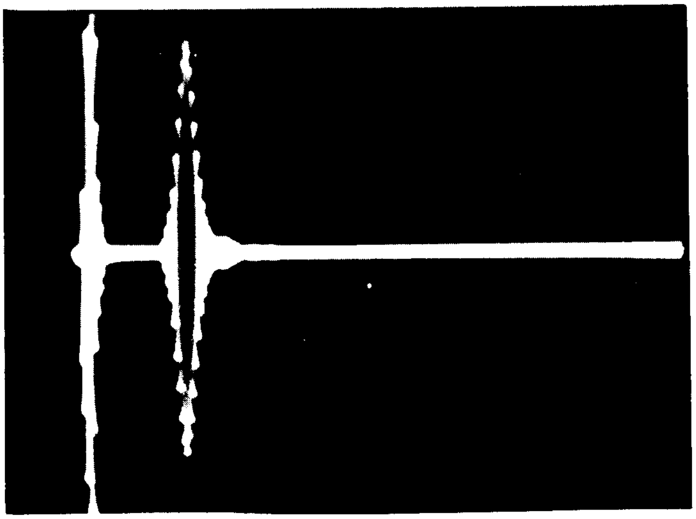


FIGURE 14 SPOT EVALUATION WITH SURFACE WAVES

Good Bond

Debond

Debond

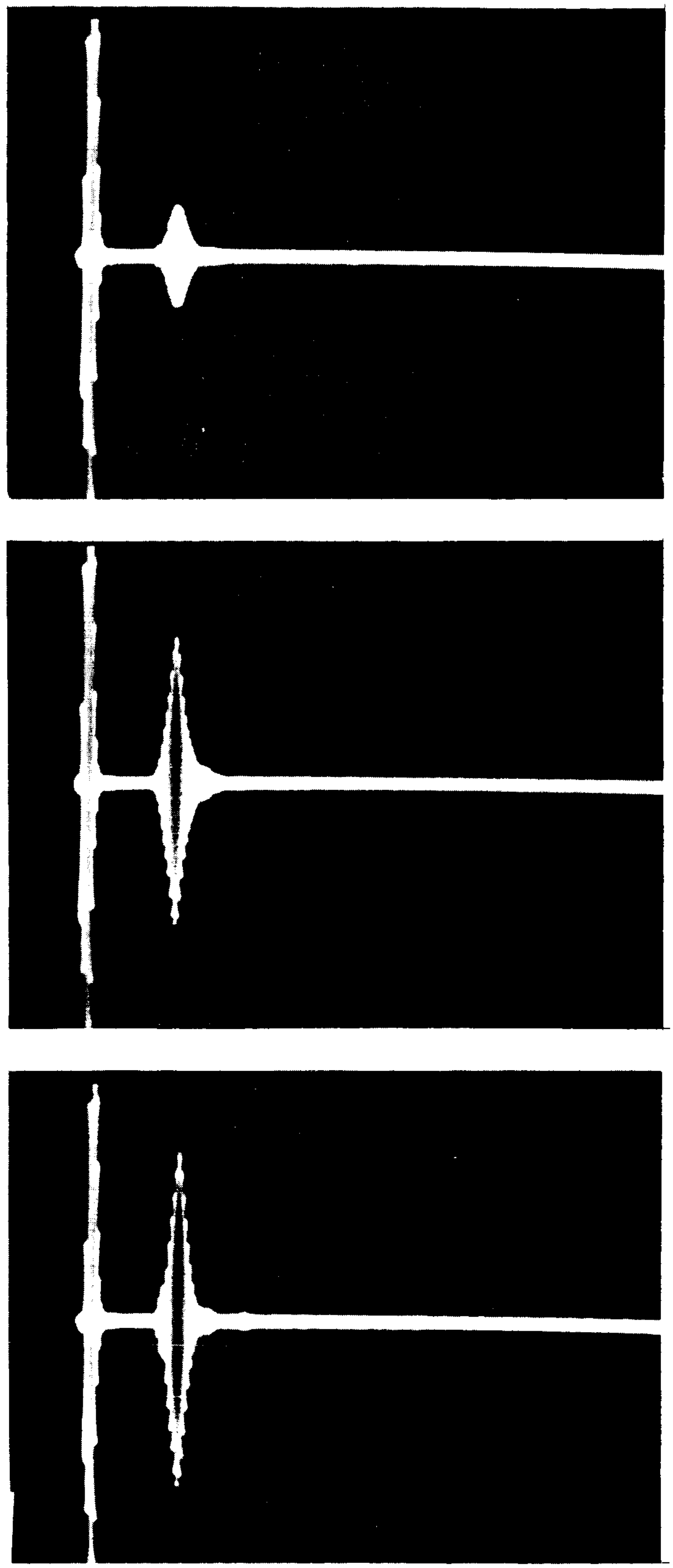


FIGURE 15 DOUBLE PROBE EVALUATION

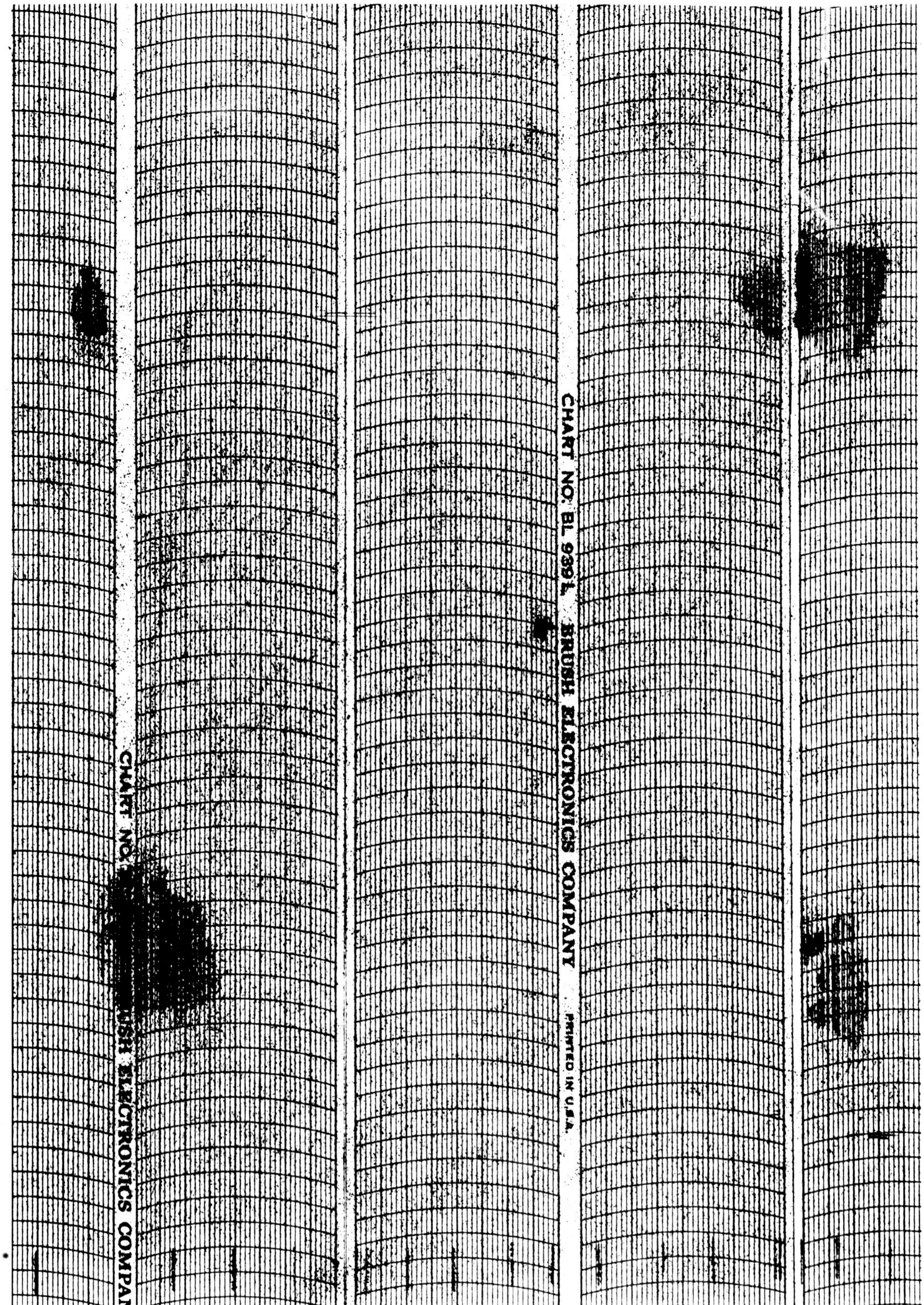


FIGURE 16 "C-SCAN" OBTAINED WITH SHOCK PULSES

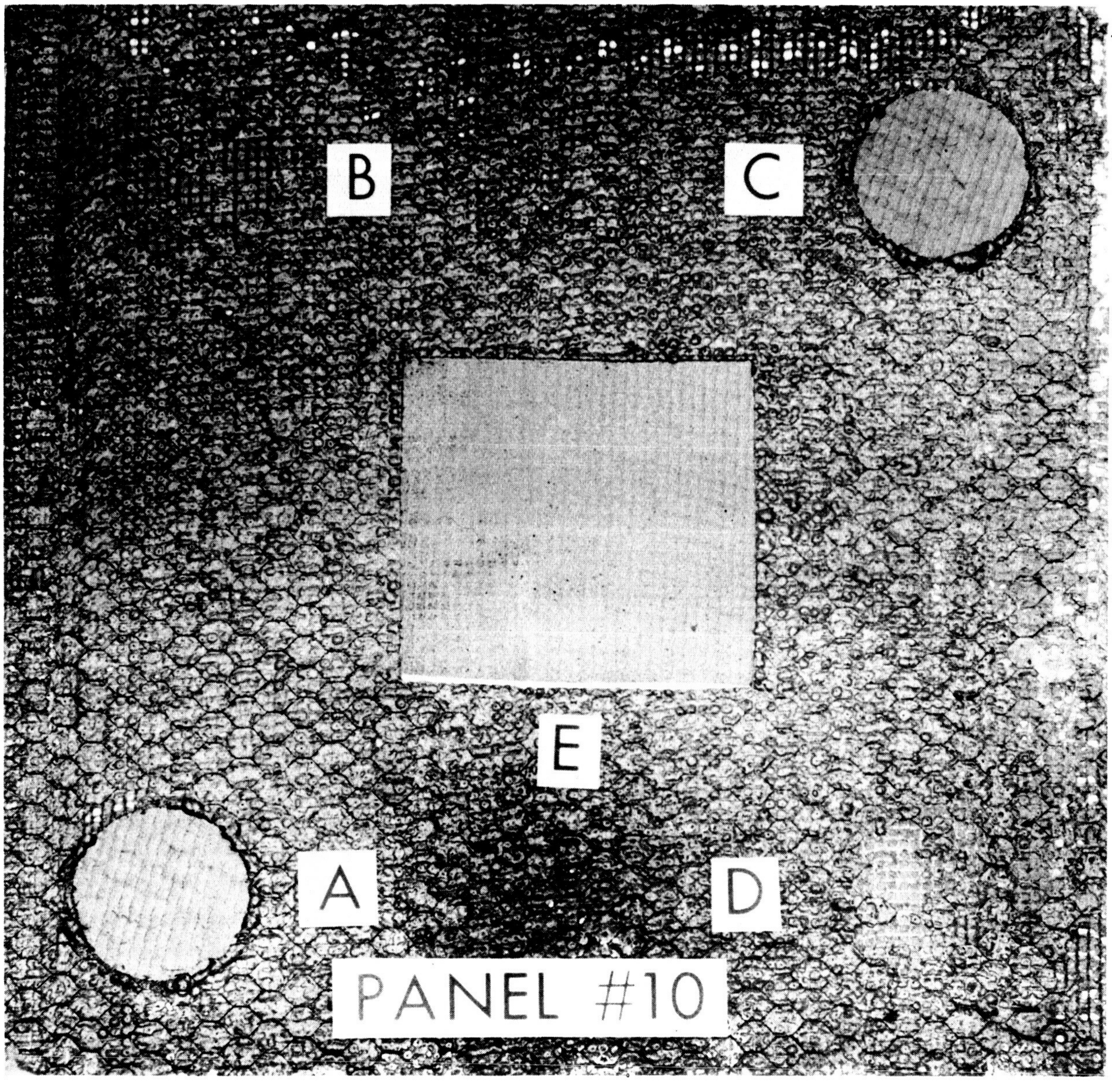


FIGURE 17 DESTRUCTIVE EVALUATION OF A REFERENCE PANEL (COVER PLATE)

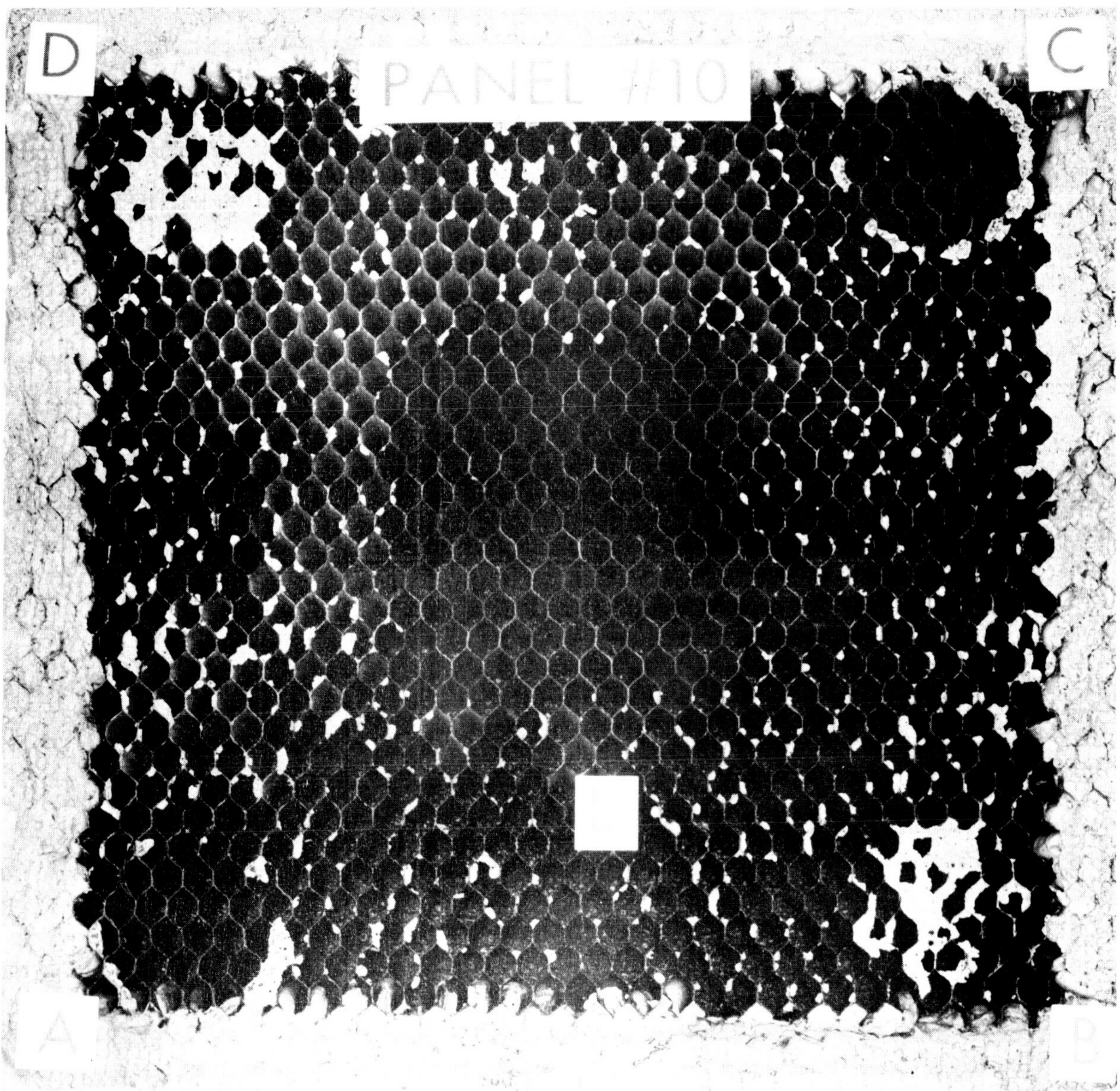
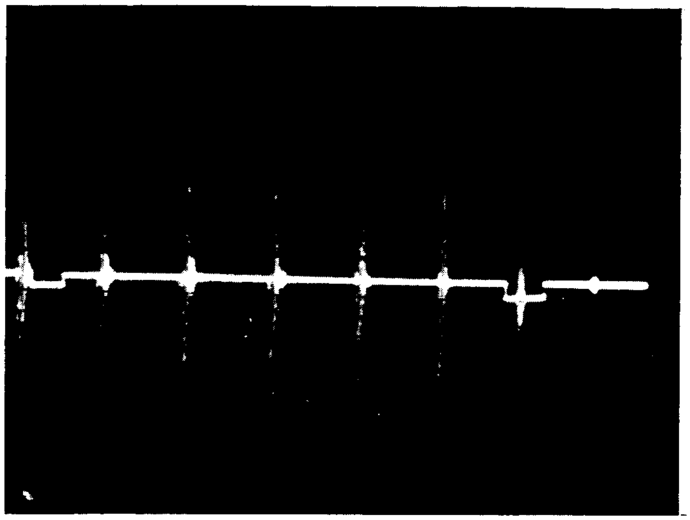
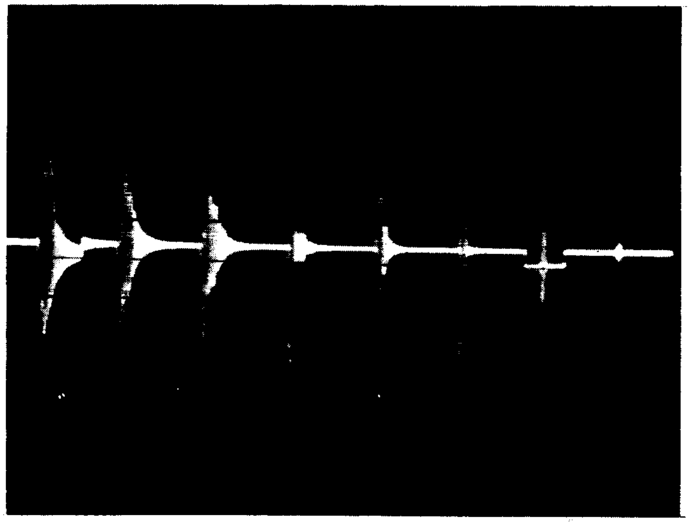


FIGURE 18 DESTRUCTIVE EVALUATION OF A REFERENCE PANEL (HONEYCOMB)

a. No Defects Indicated



b. Metal-Adhesive Debond



c. Adhesive-Core Debond

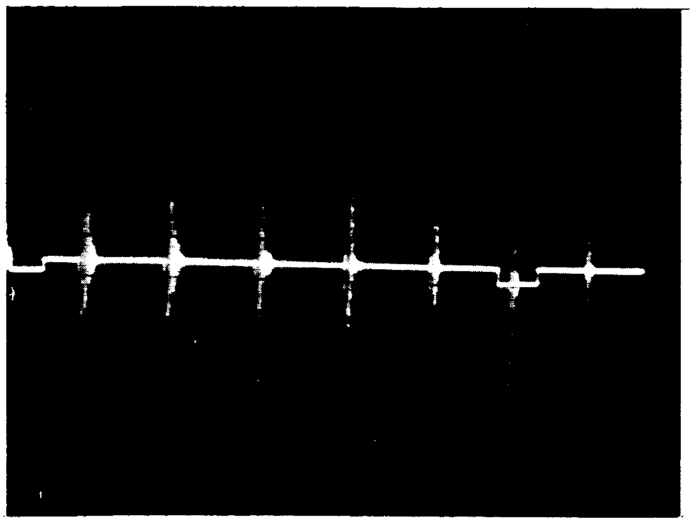


FIGURE 19 NONDESTRUCTIVE EVALUATION OF A REFERENCE PANEL

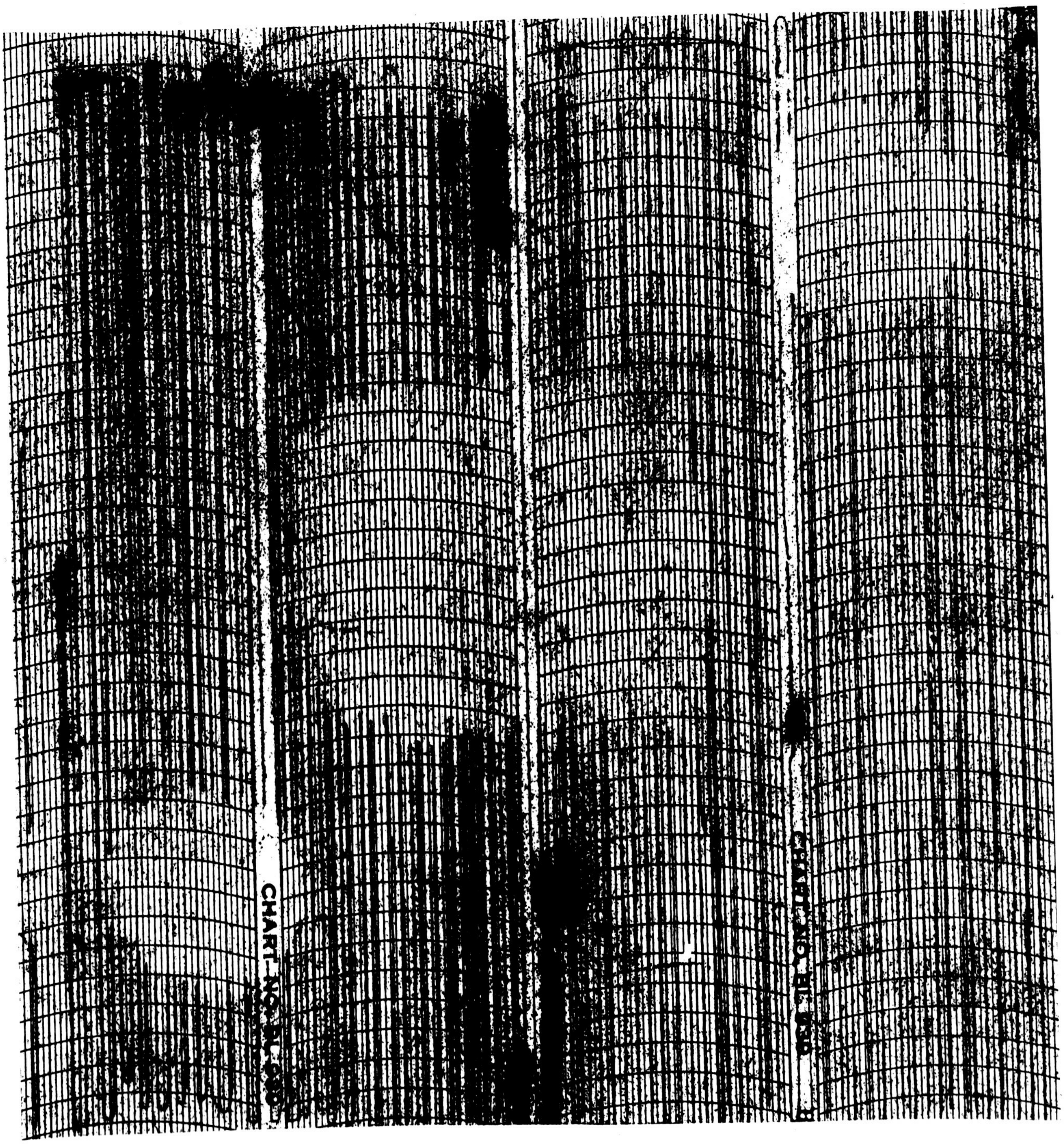


FIGURE 20a "C-SCAN" OF METAL–ADHESIVE DEBONDS

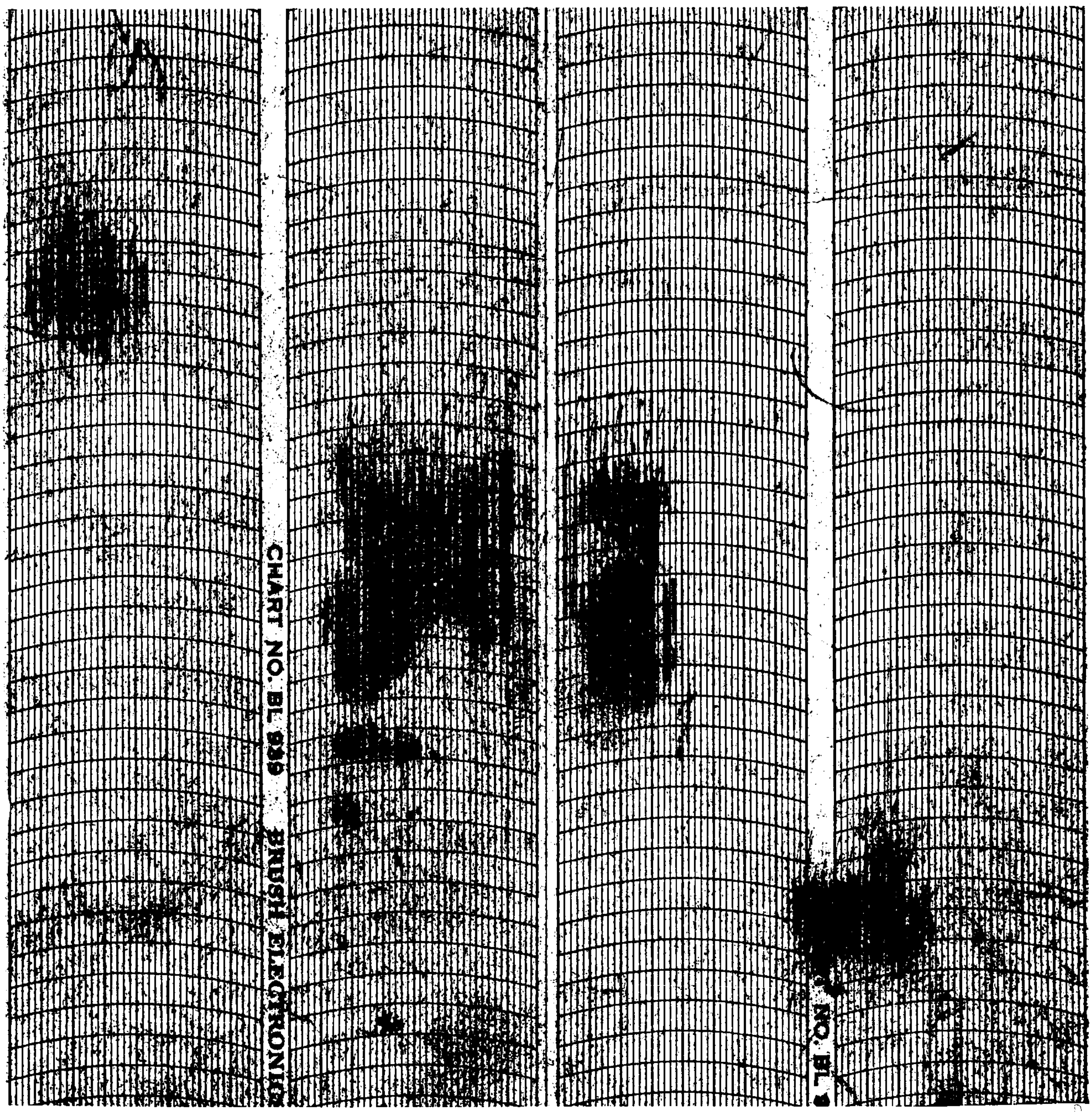
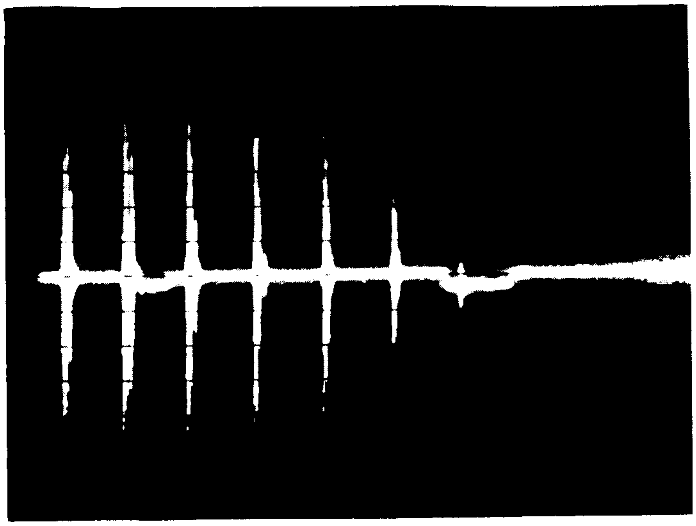


FIGURE 20b "C-SCAN" OF ADHESIVE-CORE DEBONDS

APPENDIX

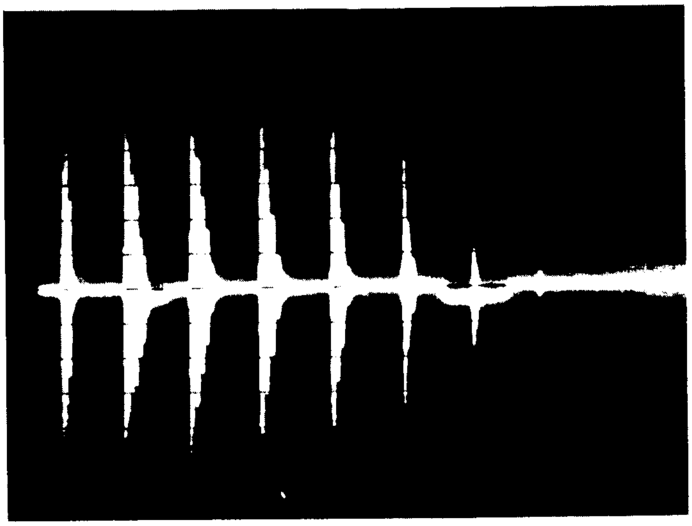
ADDITIONAL EXAMPLES OF THE "COMBINATION" INSPECTION TECHNIQUE ARE GIVEN. TECHNIQUES FOR EVALUATING INSULATING MATERIALS INVOLVING THE USE OF FOAM AND BALSA WOOD ARE DEPICTED.

Good Bond



Metal-Adhesive

Debond



Adhesive-Core

Debond

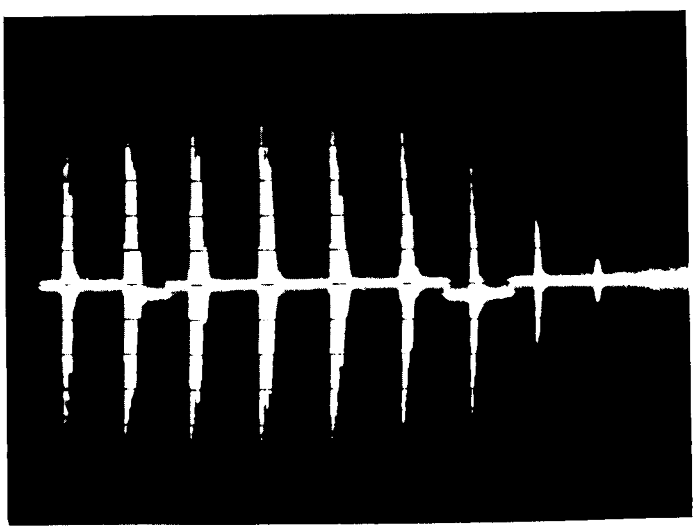


FIGURE 21 EVALUATIONS OBTAINED WITH THE COMBINATION TECHNIQUE

Core-Adhesive Debonds   Metal-Adhesive Debonds

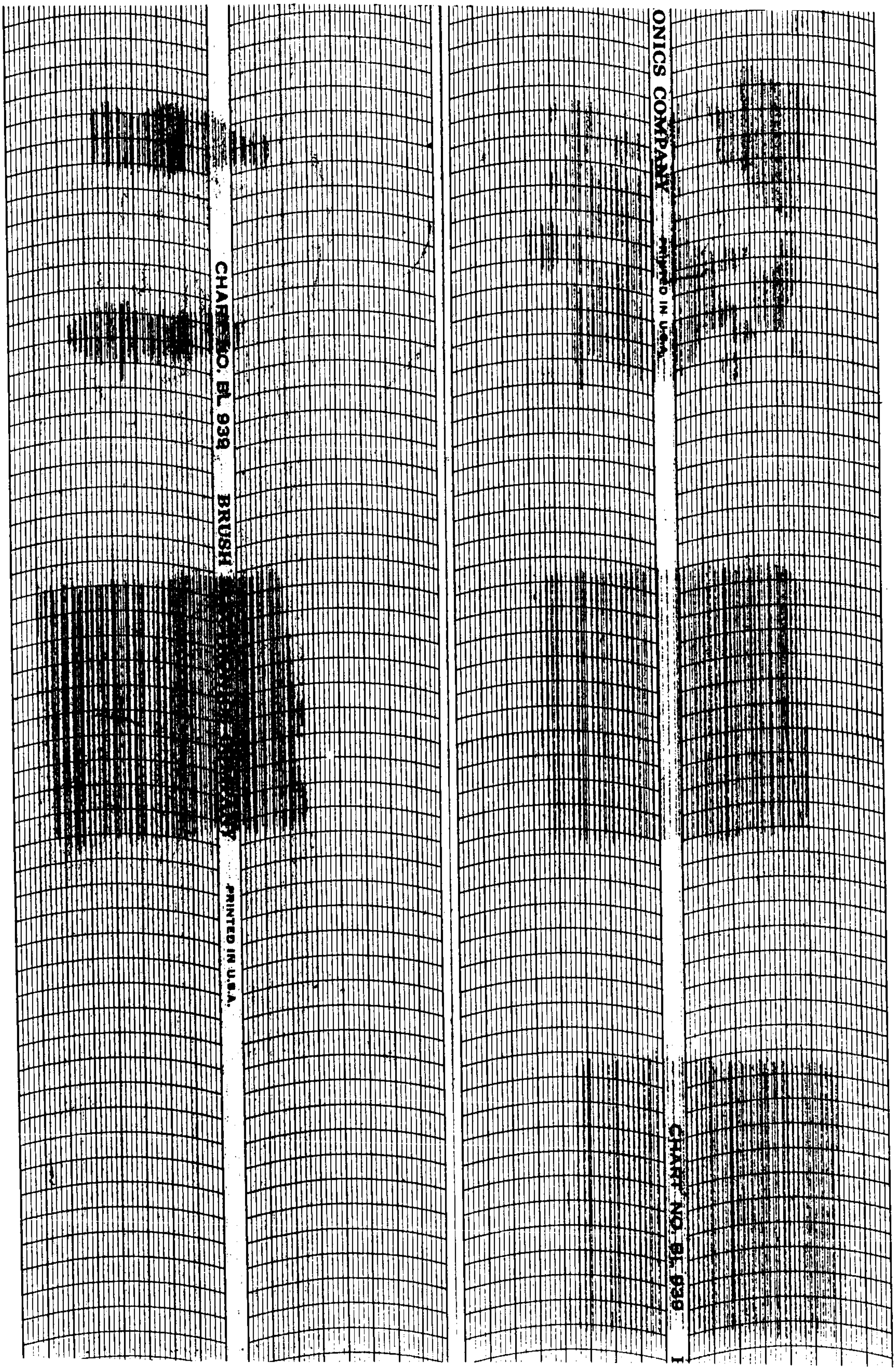
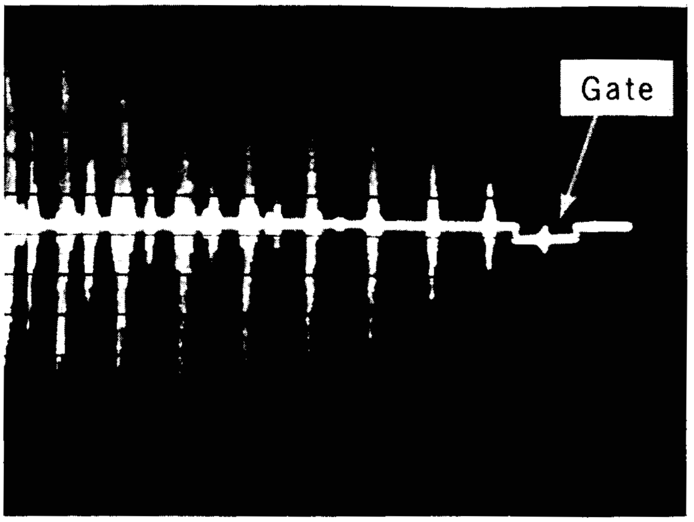
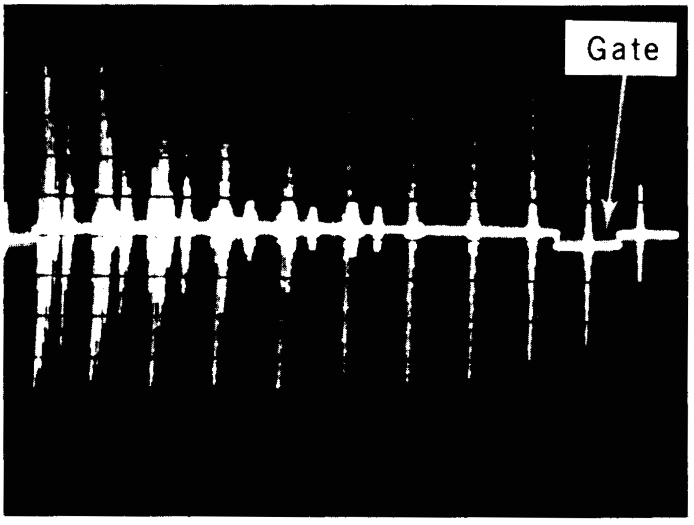


FIGURE 22 "C-SCAN"–THE COMBINATION TECHNIQUE



Good Bond



Increased Signal In The Gate Indicates

Debond Near The Core

FIGURE 23 EVALUATION OF DEBOND "D" SHOWN IN THE FOLLOWING PHOTOGRAPH

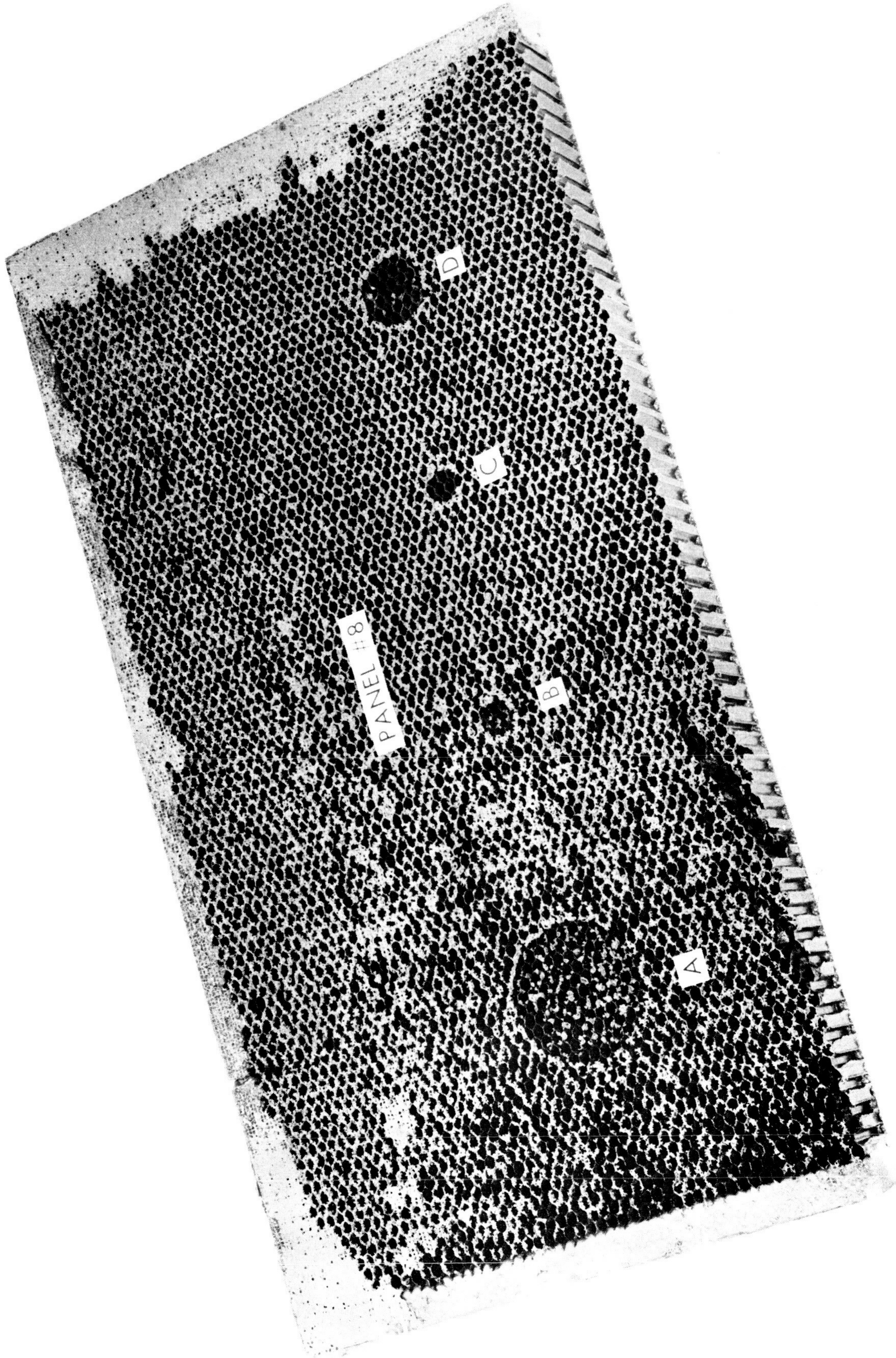


FIGURE 24 DESTRUCTIVE EVALUATION OF AN HRP PANEL (HONEYCOMB)

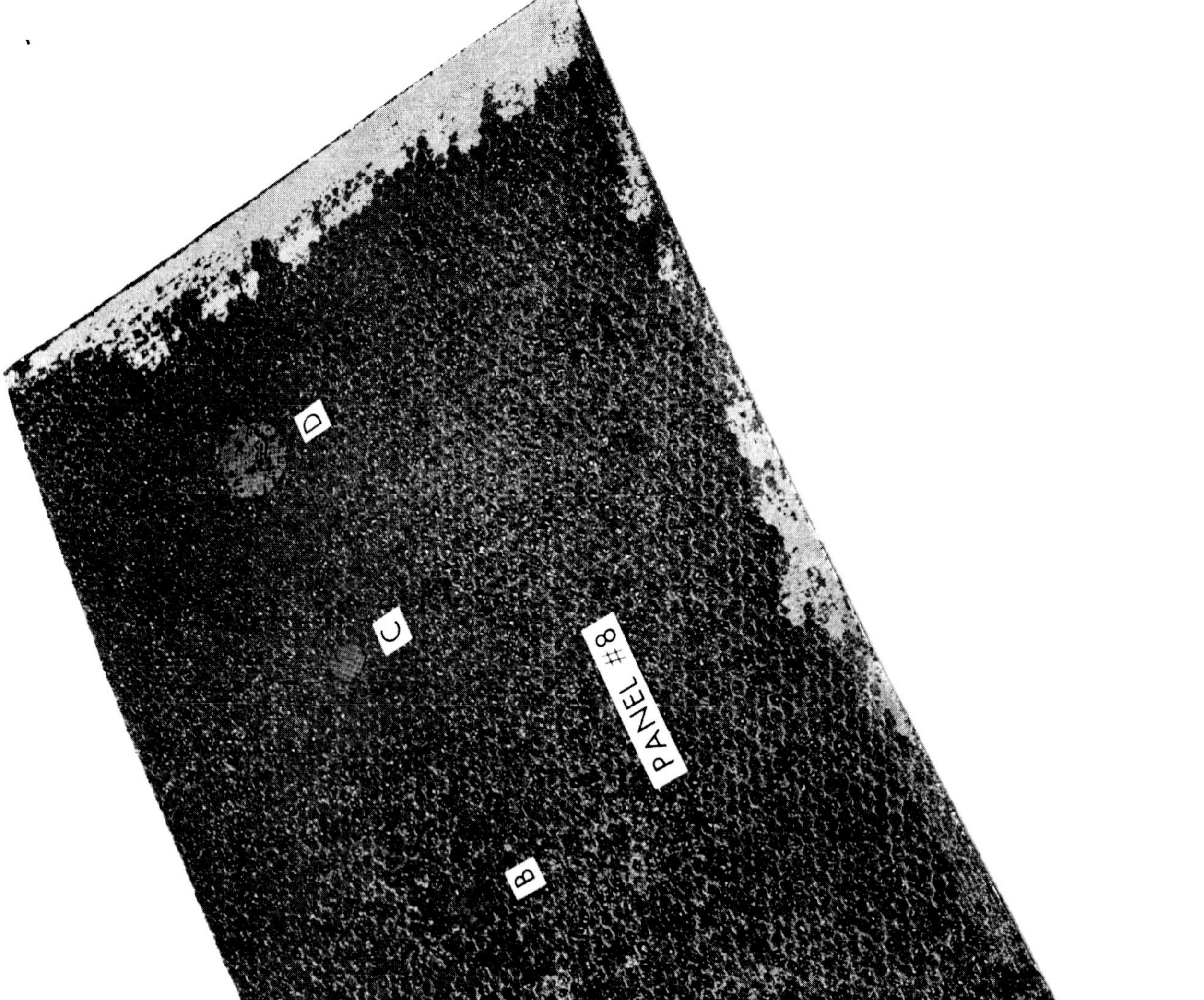
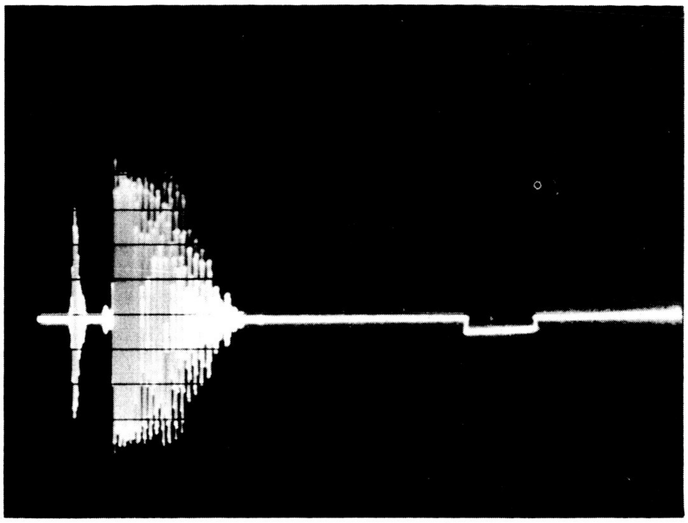
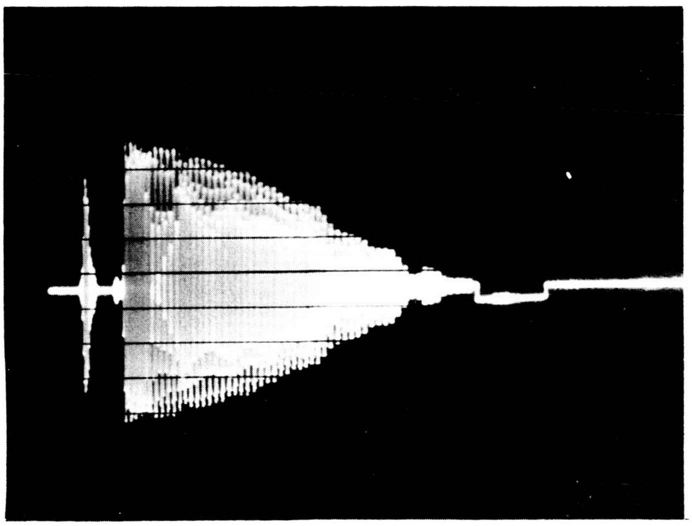


 FIGURE 25 DESTRUCTIVE EVALUATION OF AN HRP PANEL (COVER PLATE)

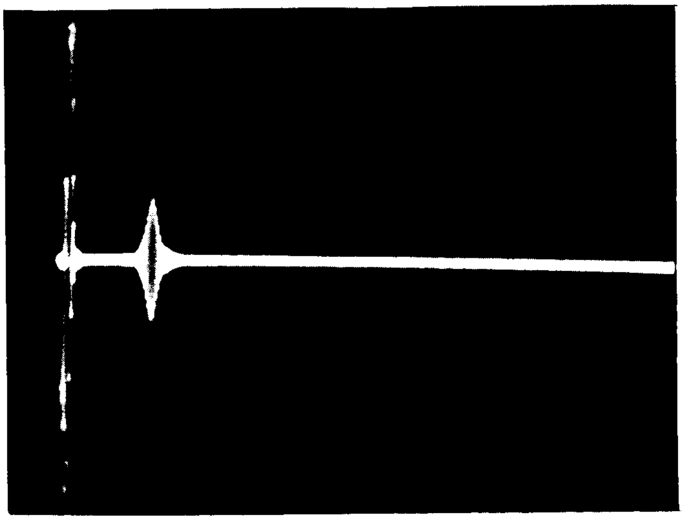


Good Bond

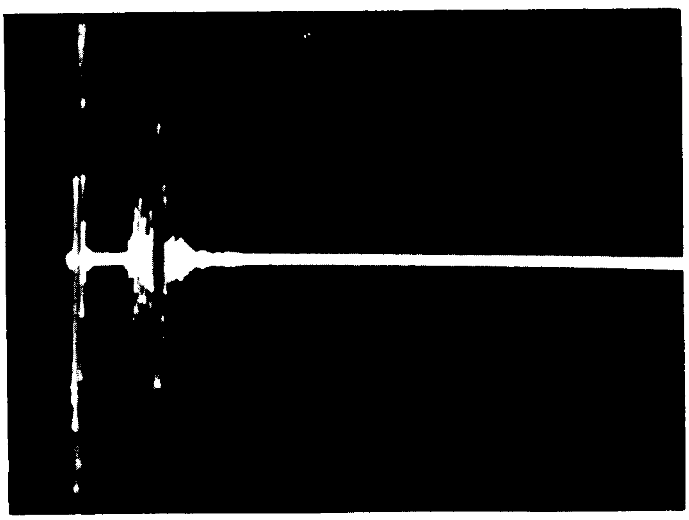


Debond

FIGURE 26 DOUBLE TRANSDUCER EVALUATION OF $\frac{3}{8}$" STEEL AND 1" BALSA WOOD COMPOSITE



Debond Near Foam



Debond Near Metal

FIGURE 27 SURFACE WAVE EVALUATION OF ALUMINUM-FOAM COMPOSITE

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ACOUSTIC TECHNIQUES FOR THE NONDESTRUCTIVE
EVALUATION OF ADHESIVELY BONDED COMPOSITE MATERIALS

By W. N. Clotfelter

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

J. E. Kingsbury

J. E. KINGSBURY
Chief, Engineering Physics Branch

W. R. Lucas

W. R. LUCAS
Chief, Materials Division

Emil A. Hellebrand

for F. B. CLINE
Acting Director, Propulsion and Vehicle Engineering Laboratory

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